COST CONSIDERATIONS FOR REINFORCED CONCRETE OFFICE BUILDING IN MALAYSIA INCORPORATING SEISMIC DESIGN

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SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2021

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By

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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

August 2021

Appendix A8

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2020/2021

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title:
Cost Considerations for Reinforced Concrete Office Building in Malaysia Incorporating Seismic Design

Name of Student:
Lim Yi Ping, Eveline

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

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Date : 2nd August 2021

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Date: 2nd August 2021	Date: 2nd August 2021

ACKNOWLEDGEMENT

The completion of this dissertation marks the end of my journey in the Bachelor of Civil Engineering study. I would like to express my sincere gratitude to those who helped and contributed their valuable time for me, leading to this research's success. First and foremost, I would like to express my appreciation to my supervisor, Ir. Dr. Shaharudin Shah Zaini, for being kind and helpful when I am facing uncertainties and difficulties. I had enhanced my knowledge on seismic design through his advice. Besides that, I would like to thank my undergraduate coursemates, Toh Wei Jian and Chan Ying Wei, who shared their knowledge and assisted me in completing this research project. I am glad to have them to keep me motivated throughout this research journey.

ABSTRAK

Malaysia adalah sebuah negara membangun di mana bangunan baharu dibina dengan pesat di bandar utama. Oleh itu, rekaan seismik mesti dipertimbangkan untuk mengatasi ancaman gempa bumi. Kebanyakan bangunan pejabat di Malaysia direka dengan pertimbangan beban graviti tetapi tidak memasukkan rekaan beban seismic. Kajian ini dijalankan bertujuan untuk menilai kesan mempertimbangkan beban seismik terhadap keperluan bahan anggota utama kerangka bangunan utama serta jumlah kos bahan berbanding beban bukan seismik. Model bangunan dengan ketinggian 10 tingkat, 15 tingkat, 20 tingkat, 25 tingkat, dan 30 tingkat telah direkabentuk menggunakan perisian ETABS. Bangunan-bangunan ini telah direka menggunakan 'EC 2' dan 'MS1553:2002' apabila tertakluk kepada beban graviti dan beban angin. Sebaliknya, 'EC 8' dan 'Malaysia National Annex' telah digunakan untuk pertimbangan seismik. Nilai PGA yang digunakan adalah 0.05g, 0.10g, dan 0.165g kerana nilai-nilai tersebut mewakili keadaan seismik yang terdapat di Semenanjung, Sarawak, dan Sabah. Keputusan menunjukkan bahawa model bangunan yang dikenakan beban seismik telah mengakibatkan kenaikan permintaan konkrit dan tetulang keluli berbanding rekaan konvensioanl. Walau bagaimanapun, peratusan kenaikan permintaan bahan berbeza dengan jenis elemen kerangka struktur. Selain itu, jumlah kos bahan ketika membandingkan rekaan seismik dengan bukan seismik berada dalam lingkungan 10% - 67% dan -4% - 60% untuk ketinggian sederhana dan tinggi. Penemuan ini disebabkan kesan beban angin ke atas bangunan tinggi menjadi lebih kritikal dan terutamanya atas tahap gempa rendah (0.05g). Kesimpulannya, apabila bangunan tinggi dikenakan beban angin, jumlah keseluruhan kos bahan akan menjadi lebih tinggi berbanding beban seismik yang menggunakan PGA yang rendah.

ABSTRACT

Malaysia is a developing country with new buildings being constructed rapidly in its major cities. As such, the seismic design must be considered to overcome possible earthquake hazards. Most of the office buildings in Malaysia are designed with gravity load considerations but not incorporating seismic design, referring to Eurocode 8. This study is carried out with the aim to evaluate the effect of considering seismic load towards the material demand for the structural frame and the overall cost compared to non-seismic load. Models with 10-storey, 15-storey, 20-storey, 25-storey, and 30-storey were designed using ETABS software. The buildings were designed using EC 2 and MS 1553:2002 when subjected to gravity load and wind load. On the other hand, EC 8 and Malaysia National Annex were used for seismic considerations. The selected reference PGA values were 0.05g, 0.10g, and 0.165g as it represents the seismicity conditions that are found in Peninsular, Sarawak, and Sabah, respectively. In general, the results showed that building models incorporating seismic design resulted in increments in concrete and reinforcement demand compared to conventional design. However, the percentage of increments in the material demand varied with the type of structural frame elements. Moreover, the total material cost when comparing seismic with non-seismic design was in the range of 10% - 67% and -4% - 60% for medium and high-rise buildings, respectively. This finding is because the wind load acting on high-rise buildings becomes more critical and particularly true for low seismicity level (0.05g). It can be concluded that, when the high-rise buildings are subjected to wind load, the total material cost will be higher when compared to seismic design adopting the low PGA level.

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LIST OF SYMBOLS

a_{gR}	Reference peak ground acceleration on type A ground
a_g	Design ground acceleration on type A ground
γ_I	Importance factor
q	Behaviour factor
q_o	Basic value of the behaviour factor
k_w	Factor reflecting the most prevailing failure mode in the structural systems with walls
α_u	Multiplier of horizontal design seismic action at formation of global plastic mechanism
α_1	Multiplier of horizontal design seismic action at formation of first plastic hinge in the system
f_{ck}	Characteristic compressive cylinder strength of concrete at 28 days
f_y	Yield strength of reinforcement
$\gamma_{G,j}$	Partial factor for permanent action j
$G_{k,j}$	Characteristic value of permanent action j
$\gamma_{Q,1}$	Partial factor for leading variable action 1
$Q_{k,1}$	Characteristic value of the leading variable action 1
$\gamma_{Q,i}$	Partial factor for variable action i
$\Psi_{0,i}$	Factor for combination value of a variable action i
$Q_{k,i}$	Characteristic value of the accompanying variable action i
$\Psi_{0,1}$	Factor for combination value of leading variable action 1
G_k	Permanent action
Q_k	Variable action
WL_x	Wind load in x-direction
WL_y	Wind load in y-direction
$\Psi_{2,i}$	Factor for quasi-permanent value of a variable action i

A_{Ek}	Characteristic value of the seismic action for the reference return period
EQ_x	Earthquake load in x-direction
EQ_y	Earthquake load in y-direction
h	Average roof height of a structure above ground
h_i	Floor to floor height of the structure

LIST OF ABBREVIATIONS

PGA	Peak Ground Acceleration
BS	British Standard
EC 8	Eurocode 8
EC 2	Eurocode 2
NA	National Annex
MS	Malaysian Standard
ULS	Ultimate Limit State
SLS	Serviceability Limit State
DCL	Ductility Class Low
DCM	Ductility Class Medium
DCH	Ductility Class High
SRSS	Square Root of The Sum of Squares
CQC	Complete Quadratic Combination
RC	Reinforced Concrete
IEM	Institute of Engineer Malaysia
2-D	Two-Dimensional
3-D	Three-Dimensional

CHAPTER 1

INTRODUCTION

1.1 Background

Earthquakes occur as the earth's surface vibrates due to sudden motions of the earth's crust, which is made up of a number of dense rock plates that float on the molten (Balendra, 1993). Seismic waves are generated when shear stress exceeds the strength of the rock, causing a rupture along the fault line as plates drift along convection currents. Earthquakes can alter the structural stability of buildings. Seismic waves strike on the building by moving the base back and forth since the foundation is the point of contact between the building and the ground. The building's mass opposes this motion, creating inertia forces both vertically and horizontally in the structure (Balendra, 1993).

Malaysia is located on the stable Sunda Plate, but the seismically active Sumatran Subduction Zone and the Sumatran Fault trigger minor earthquakes, as shown in Figure 1.1. Due to Malaysia's geographical position, which is not near plate tectonic borders and far away from the Ring of Fire, significant earthquakes and volcanic eruptions are thought to be rare. The distance of the closest potential earthquake epicentre may be located at a distance; however, a very low peak ground acceleration from a distant earthquake might lead to disastrous events due to the occurrence of large displacement properties (Balendra et al., 2002).

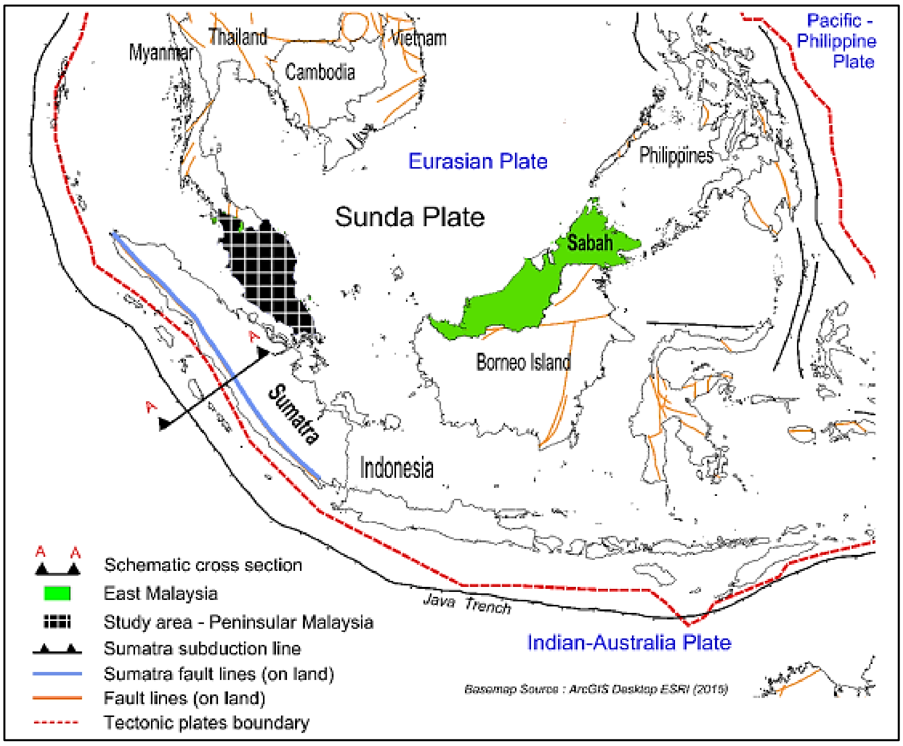


Figure 1.1: Location of Malaysia on the Sunda Plate and Tectonic Plates Surrounded Malaysia (Loi et al., 2018)

The reformation of the Sunda-land core, as shown in Figure 1.2, enables geologists to infer that the occurrence of local origin earthquakes in Peninsular Malaysia is a symptom of the reactivation of inactive ancient faults (Marto et al., 2013). Cities in Peninsular Malaysia's central west, between latitudes 2 to 4, are more vulnerable to high peak ground acceleration (PGA) because they are closer to the seismically active Sumatran zone (Loi et al., 2018). Furthermore, since 1874, Sarawak and Sabah have experienced 21 and 94 earthquakes, respectively, indicating a different scenario from Peninsular Malaysia (Marto et al., 2013). These earthquakes have triggered significant events such as landslides which caused considerable structural and non-structural damages. Therefore, Malaysia's overall low seismic hazard should be taken seriously as the neighbouring countries such as Indonesia and Philippine are classified as high seismicity regions.

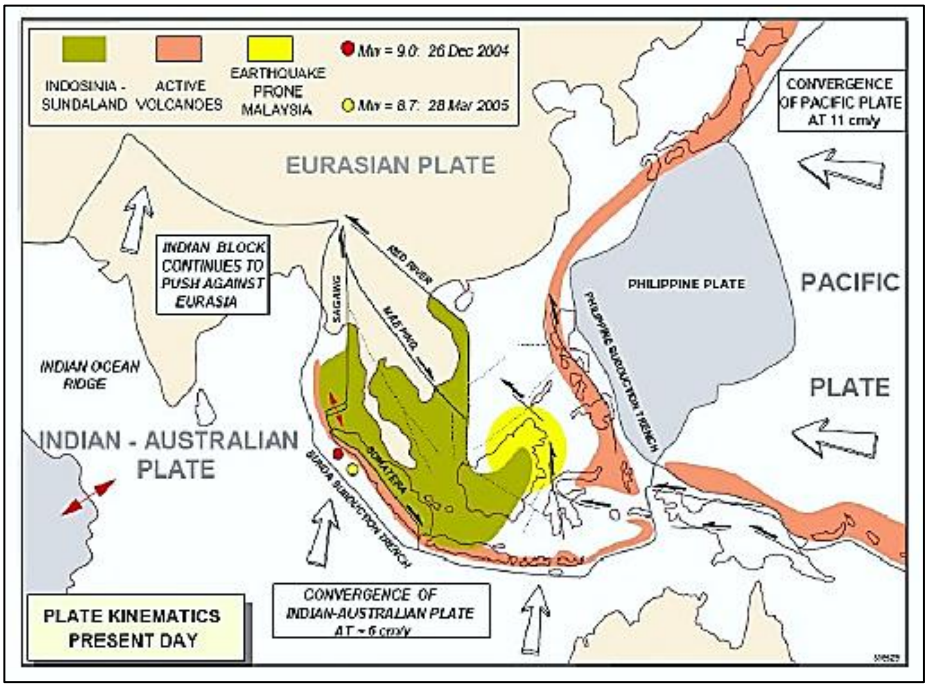


Figure 1.2: Earthquake-prone Region of Malaysia (Marto et al., 2013)

Since Malaysia is a developing country with new buildings being constructed at a rapid pace in its major cities, the seismic design must be prepared for possible earthquake hazards. Most of the office buildings in Malaysia are designed with gravity load considerations but not incorporating seismic design referring to Eurocode 8 (EC 8) and Malaysia National Annex. However, reinforced concrete buildings with seismic design in Malaysia are now taken more seriously due to past significant events and the availability of seismic design parameters. When new buildings are built to accommodate different PGAs for seismic design (depending on location), there will be cost implications on the material costs, especially for the main structural frames. This study focuses on the cost comparison for reinforced concrete buildings subjected to non-seismic and seismic design considerations. Attentions are given to the design demand for beam, column, and wall. The reference PGA and building height are considered as the variables for this study.

1.2 Problem Statement

Malaysia is a developing country and moving towards becoming a developed country in the future. As such, projects related to infrastructures, housing, public amenities and developing new townships are important for the development of Malaysia. Construction of buildings for this development purposes is part and parcel of the vision. Almost all existing buildings in Malaysia are designed without adopting seismic considerations; such buildings are designed considering only various vertical loads and wind load combinations according to British Standard, BS 8110:1997. The leading factor to this might be Malaysia's location, which is anticipated to be at a low seismicity area. During this period, engineers and relevant technical agencies are not required to consider seismic load in the design as it is not yet mandatory. However, the earthquake incidents that hit Ranau and Kundasang with a magnitude of 6.0 had triggered the Malaysian Government to emphasise seismic design for future building constructions especially with the establishment of MS EN1998-1:2015 (NA-2017).

By adopting seismic design in the future, there might be a price to pay from the economic point of view: having more expensive buildings. If the seismic design is considered in Malaysia, there is still a shortage of reliable information on building material costs. Past studies on material cost have varied percentage difference in concrete volume and quantity of steel reinforcement. With the scattered results pertaining to the cost of incorporating seismic design, there is still lack of a systematic approach in this area related that could provide accurate information and assist the relevant construction players in Malaysia.

1.3 Objectives

The objectives of this research are as below:

1. To determine the material demand of structural members due to the effect of various PGA and building heights.
2. To evaluate the effect of incorporating seismic design on the total material cost.

1.4 Scope of Work

The scope of work involves the modelling, analysis, and design of rectangular office building models with different heights subjected to Eurocode 2 (non-seismic), and Eurocode 8/ NA-2017 (seismic). The buildings' proposed heights are categorized into 10-storey, 15-storey, 20-storey, 25-storey, and 30-storey. The three-dimensional (3-D) frame models will be generated using ETABS version 2018 software package for the analysis and design.

In the case of non-seismic design, the lateral force is in the form of wind load complying with MS 1553:2002. The seismic design will be performed in accordance with EC8/ NA-2017 based on modal spectrum analysis, where the design spectrum will be generated from the elastic response, reference PGA, and other seismic actions. Several values of reference PGA that are representing the level of seismicity in Malaysia will be used, namely 0.05g, 0.10g, and 0.165g.

This study considers the material demand of the building's main frame: the beam, column, and wall, in terms of concrete volume and reinforcement weight. The slab serves as a rigid diaphragm and is not design under seismic load because no code allows designing a slab using such loading. The overall material cost of the main frame is the combination of all materials being considered and multiplied by the relevant unit price.

1.5 Dissertation Outline

This dissertation comprises of five chapters and organized as follows:

Chapter 2: Literature Review. This chapter presents the review of seismic activities in Malaysia and the factors contributing to structural damages during earthquake events. In addition, the seismic design approach for reinforced concrete building using Eurocode 8 and Malaysia National Annex is presented, and studies related to cost considerations for non-seismic and seismic design based on previous research are reviewed.

Chapter 3: Methodology. This chapter presents the development of 3-D building models using ETABS software. The procedures for modelling, analysis, and design of rectangular reinforced concrete buildings subjected to non-seismic and seismic loads, and the method to obtain the material cost are discussed. This chapter covers the explanation on the relevant parameters required for the analysis and design of the office building models.

Chapter 4: Results and Discussion. This chapter presents the analysis and design results of all building models incorporating the non-seismic or seismic design. The percentage difference in terms of concrete volume and reinforcement weight for beam, column, and wall between the non-seismic and seismic designs are calculated and presented in this chapter. In addition, the total material cost of the structural frame is determined and compared accordingly.

Chapter 5: Conclusions and Recommendations. This chapter provides the conclusions and suggestions for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter explains about the seismic activities in Malaysia and the factors contributing to structural damages during earthquake events. Moreover, the seismic design approach for reinforced concrete building using Eurocode 8 and Malaysia National Annex is presented. This chapter also reviews past researchers' works on cost considerations for non-seismic and seismic design.

2.2 Seismic Activities in Malaysia

Peninsular Malaysia's tectonic plate is located between Australia and Eurasian plates, while East Malaysia's is placed between the Philippine Sea plate and the Eurasian plate. The earthquakes' tremors from neighbouring countries such as Indonesia and the Philippines and local origin earthquakes can still be felt, even though Malaysia is located on the inactive Sunda Plate and low seismicity zone. In addition, Malaysia is located outside of the Ring of Fire (refer to Figure 2.1). Active volcanoes represent the Pacific Ring of Fire in red dots that are formed along tectonic plate boundaries.

Figure 2.1: Active Volcanoes, Plate Tectonics, and the Ring of Fire (Azmi et al., 2021)

The 9.0 magnitude earthquake that struck Acheh, Indonesia, in 2004 killed 76 people and damaged a large number of properties in Peninsular Malaysia (Adiyanto et al., 2014). In 2007, approximately twenty-four tremors of magnitude 0.3 - 0.42 were documented in Bukit Tinggi, Pahang. Similarly in 2009, earthquake activities were recorded in places such as Jerantut in Pahang, Manjung in Perak, and Kuala Pilah in Negeri Sembilan.

Recently, the Ranau earthquake has been the centre of attention. The earthquake event with a magnitude of 5.9 Richter scale shocked Malaysia with 18 deaths and damages to some buildings and infrastructures. The damage due to this earthquake in Sabah was estimated to cost approximately RM100 million (Sabah Earthquake, 2015). The interaction of three major tectonic plates is currently compressing Sabah and these plates are situated on the south-eastern edge of the Eurasian Plate, bordered by the Philippine Plate and the Pacific Plate. The Philippine Plate and Pacific Plate are colliding with the Eurasian Plate at about 10 cm per year. Since the earthquake's epicentre was near Mount Kinabalu's peak, the focus of the quake was beneath the peak (Tongkul, 2015). As a result, East Malaysia, especially Sabah, has been regarded as a moderate seismicity area.

2.3 Factors Contributing to Structural Damages During Earthquake Events

The medium or high-intensity magnitude earthquakes can impose significant damages to the structures. The inappropriate structural configurations are reasons buildings being damaged or collapsed during earthquake events. The factors contributing to the damage or failure of a building are discussed in the following sub-sections.

2.3.1 Presence of Soft Storey

Reinforced concrete buildings with soft and weak storey mechanism tend to collapse during seismic events. Figure 2.2 shows a typical building categorized as soft first storey and “pilotis” configuration. This structural configuration is largely applied in existing buildings as it allows optimum distribution of space at the ground floor but not recommended from a seismic point of view. The soft first storey indicates that the stiffness and strength of the first floor are significantly lower than the upper floors, leading to the concentration of lateral displacements on the first floor (Alih and Vafaei, 2019). The partial or total collapse can occur at the soft storey when the lateral strength changes suddenly between adjacent stories due to lack of removing partition walls or decreasing the cross-section of columns (Yön et al., 2017). Therefore, the inter-storey drift due to soft storey is likely to happen during earthquake events and an example of such damage is shown in Figure 2.3.

Figure 2.2: Typical "Pilotis" Configuration Observed for the RC Buildings (Alih and Vafaei, 2019)

Figure 2.3: Inter-Storey Drift during Earthquake Events (Yön et al., 2017)

2.3.2 Inadequate Amount of Shear Reinforcement

The inadequate transverse reinforcement in column and beam is also one of the factors causing damages in structures. During an earthquake, structural elements usually fail due to the shear force that exceeds the allowable limit. The presence of high shear forces during an earthquake, especially at column and beam-column joints can lead to failures, as shown in Figure 2.4 (Yön et al., 2017). This type of damage can be arrested by providing sufficient transverse reinforcement.

Figure 2.4: Damaged Structure Due to Inadequate Shear Reinforcements Spacing (Yön et al., 2017)

2.3.3 Presence of Weak Column - Strong Beam

When deep and rigid beam is used with flexible columns, a weak column–strong beam failure mechanism during an earthquake event is developed. Figure 2.5 shows a severe crack pattern due to this mechanism. The deep and rigid beam may cause plastic hinge at column when the column has a smaller resistance moment than beam (Alih and Vafaei, 2019). The sum of moments at the column connected to any joint should be higher than the sum of moments at the beam connected to the same joint to prevent this unfavourable effect.

Figure 2.5: Weak Column-Strong Beam for RC Building (Alih and Vafaei, 2019)

2.4 Eurocode 8 and Malaysia National Annex

EN 1998-1, "Design of Structures for Earthquake Resistance," specifies how to design buildings and other structures in a systematic way. EC 8 is aimed at protecting human lives, minimize damage, and ensure that civil protection systems remain operational after an earthquake. As a result, no-collapse and damage-limitation are the most important design and execution criteria.

The ultimate limit states (ULS) or no-collapse requirement prevents collapse during the worst credible incidents (1:475 years) while allowing some forms of structural damage. This limit state is satisfied by a structural system that has both lateral resistance and energy-dissipation capability. The design seismic action for local collapse prevention is based on the probability of 10% chance of exceeding in 50 years, corresponding to a 475-year mean return period.

Damage limitation requirements, also known as serviceability limit states (SLS), are designed to avoid structural damage and limit no-structural damage during the most likely occurrence in a structure's lifetime (1:95 years). SLS can be met by using linear behaviour to provide sufficient stiffness and strength. Seismic action with a 10% chance of exceeding the design limit in 10 years, corresponding to a 95-year mean return period (Eurocode 8, 2004).

2.4.1 Ground Types

Ground types A, D, and E in EC 8, as shown in Figure 2.6, are the valid ground type classifications applicable to Malaysian conditions when the total ground depth does not exceed 30 m. Malaysia National Annex to EC 8 has limited the application of the ground types' classification to soil sites where the total depth of soil sediments overlying bedrock does not exceed 30 m. Ground type S1 and S2 are also irrelevant to Malaysia. A brief description of ground types A, D, and E is shown in Table 2.1.

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	_	_
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	_	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

Figure 2.6: Ground Types (Eurocode 8, 2004)

Table 2.1: Ground Types A, D, and E (Looi et al., 2018)

Ground Type	Description
A	Rock or very shallow soil sites overlying bedrock
D	Soft shallow soil sites
E	Stiff shallow soil sites

The site natural period parameter, *Ts*, which is proportional to the total depth of the soil sediment and inversely proportional to the average value of the shear wave velocity of the soil material, *Vs*, determines site classes in NA-2017. Figure 2.7 shows the site classification that addresses the concern of site response behaviour of deep soil sediments, where the total thickness of the soil sedimentary layers overlying bedrock exceeds 30 m (Looi et al., 2018). Buildings constructed on ground type which is soft and weak might experience greater amplification during earthquake and the need of improvisation on design considerations will lead to construction cost increment (Hong et al., 2020). Soil type representing a site condition will have a higher cost effect if the soil is categorized as soft soil (Roslan et al., 2019).

Ground type	Description and range of site natural period, T_S (s)*
A	Rock site, or a site with very thin sediments and T_S < 0.15 s
B	A site not classified as ground type A, C, D or E
C	A site with sediments of more than 30 m deep to bedrock and T_S = 0.5 s to 0.7 s
D	A site with sediments of more than 30 m deep to bedrock and T_S = 0.7 s to 1.0 s
E	A site with sediments of more than 30 m deep to bedrock and T_S = > 1.0 s, or deposits consisting of at least 10 m thick of clays/silts with a high plasticity index (PI > 50)

Figure 2.7: Ground Classification Scheme in Accordance to Site Natural Period, T_s for Soil Deposit Exceeding 30 m in Depth (Malaysia NA, 2017)

2.4.2 Ductility

The ability of a structure to withstand significant deformations beyond the yield point without breaking after being subjected to specific loadings is known as ductility. In the field of earthquake engineering, it is expressed in terms of demand and availability. The available ductility is the maximum ductility that the structure can withstand without damage, while the ductility demand is the highest ductility that the structure can achieve during an earthquake incident (Ductility Class in Eurocode 8, n. d.).

Low, medium, and high energy absorption are the three levels of energy absorption. Ductility class low (DCL) achieves seismic resistance without requiring delayed ductility. It predicts the design of members with seismic loading from the design seismic action (of 475 years) with a behaviour factor of 1.5 and reinforcement estimates similar to non-seismic activities. Therefore, EC 8 recommends that DCL to be used only in areas with low seismic activity, as it does not provide an adequate level of protection for buildings in high seismicity areas (Ductility Class in Eurocode 8, n. d.). Furthermore, ductility class medium (DCM) allows for high levels of ductility, while ductility class high (DCH) allows for even higher levels of ductility following by complex design demands with a behaviour factor greater than 4.

Figure 2.8 shows the values of basic behaviour factor, q_o depending on its structural types and ductility cases. For the purpose of energy dissipation capacity, the behaviour factor, q can be derived from the following equation:

$$q = q_o k_w \geq 1.5 \tag{2.1}$$

where,

q_o = the basic value of the behavior factor, which varies depending on the type of the structural system and on its regularity in elevation as shown in Figure 2.8 for buildings regular in elevation

k_w = the factor reflecting the most common failure mode in the structural systems with walls; k_w = 1.0 for frame and frame equivalent dual systems

STRUCTURAL TYPE	DCM	DCH
Frame system, dual system, coupled wall system	$3,0\alpha_u/\alpha_1$	$4,5\alpha_u/\alpha_1$
Uncoupled wall system	3,0	$4,0\alpha_u/\alpha_1$
Torsionally flexible system	2,0	3,0
Inverted pendulum system	1,5	2,0

Figure 2.8: Basic Value of The Behaviour Factor, q_o, for Systems Regular in Elevation (Eurocode 8, 2004)

The values of α_u/α_1 shown in Table 2.2 can be used for buildings with frame or frame-equivalent systems and building plan regularity.

Table 2.2: Value of α_u/α_1 (Eurocode 8, 2004)

Building Type	α_u/α_1
One-storey	1.1
Multi-storey, One bay frame	1.2
Multi-storey, Multi-bay frames or frame-equivalent dual structures	1.3

2.4.3 Reference Peak Ground Acceleration (PGA)

The peak ground acceleration is the most direct measurement of ground motion. Seismic design can be overlooked if the bedrock peak ground acceleration has a 10% chance of being exceeded in the next 50 years is less than 0.04g. For higher seismic ground motion, simpler rules that eliminate ductile detailing can be used if the bedrock peak ground acceleration has a 10% chance of being surpassed in the next 50 years is less than 0.08g (Eurocode 8, 2004). The full provisions of EC 8, including ductile detailing requirements, are recommended for more severe seismic ground motions.

It is also well established that the response buildings are dependent on the frequency content. Defining seismic ground motion in terms of response spectra is a conventional practice that represents the peak elastic response of structures as a function of their modal periods (Housner, cited in Pappin, 2011). Pappin et al. (2011) suggested that PGA is insufficient to describe seismic ground motion because it ignores the motion's frequency content. The fundamental period, which is equivalent to the number of storeys divided by ten, is sufficient to define the seismic response of buildings up to about ten storeys. Full elastic dynamic analyses are also needed for higher buildings, as their higher mode responses are often important.

The reference PGA on ground type A used in Malaysia is derived from contour maps in NA-2017. The design ground acceleration on ground type A can be obtained with the multiplication of importance factor and reference PGA as shown in Equation 2.2.

$$a_g = \gamma_I * a_{gR} \tag{2.2}$$

Recommended values of importance factor in Malaysia are shown in Figure 2.9. Office buildings are usually highly occupied, leading to a higher death rate when disaster happens. Therefore, it should be designed to have better resistance towards destruction compared to ordinary buildings (Fardis et al., 2015).

Building importance class	Importance factor 1 (γ_I)	Recommended building categories
I	0.8	Minor construction
II	1.0	Ordinary buildings (individual dwellings or shops in low rise buildings)
III	1.2	Buildings of large occupancies (condominiums, shopping centres, schools and public buildings)
IV	1.5	Lifeline built facilities (hospitals, emergency services, power plants and communication facilities)

Figure 2.9: Importance factor in Malaysia (Malaysia NA, 2017)

2.5 Modal Response Spectrum Analysis (Linear Dynamic)

A response spectrum gives, by definition, the maximum absolute values of a response quantity (in seismic analysis, this is typically acceleration, velocity, and displacement) as a function of the period, T_n (or a related quantity such as the frequency ω_n), for a fixed damping ratio and a given ground motion. A structure's response may only describe well if the deformation is defined by more than one degree of freedom. Hence multiple degrees of freedom systems are considered. For a rigid diaphragm building, the deformation of a building under earthquake loading may be described just by two horizontal degrees of freedom at each storey, plus the twisting rotation around a vertical axis. Besides that, several vibration modes contribute to the structural response. There are several approaches for the combination of responses in different vibration modes, Square Root of the Sum of Squares (SRSS) and Complete Quadratic Combination (CQC) (Fardis et al., 2015).

It is necessary to consider the response of all vibration modes that contribute significantly to the global response. If the sum of the effective modal masses for the modes are taken into account at least 90% of the total mass of the structure, this principle is said to be satisfied (Eurocode 8, 2004). Modal response spectrum analysis can be used on any structure, including those of various shapes. This response spectrum method is a commonly used method for analysis. The dynamic analysis method is encouraged in EC 8 and regarded as the ‘reference method’ in view of the availability of commercial packages possessing dynamic analysis capability (Looi et al., 2015).

2.6 Building Model

Modelling of the buildings is conducted before the beginning of full analysis. It can be carried out using a two-dimensional (2-D) or three-dimensional (3-D) model depending on the computational time and the level of accuracy required. However, 3-D modelling usually provides a more realistic analysis as translational and rotational movement of all directions are considered.

Ramli et al. (2017) conducted a research using 3-D models. The analysis and design are based on structural frame elements (beam and column) for 5-storey and 10-storey buildings using ETABS software. The frame models used for design and analysis are as shown in Figure 2.10. Adiyanto et al. (2019) modelled 6-storeys building using a three-dimensional (3-D) approach, generated using Tekla Structural Designer software, as shown in Figure 2.11.

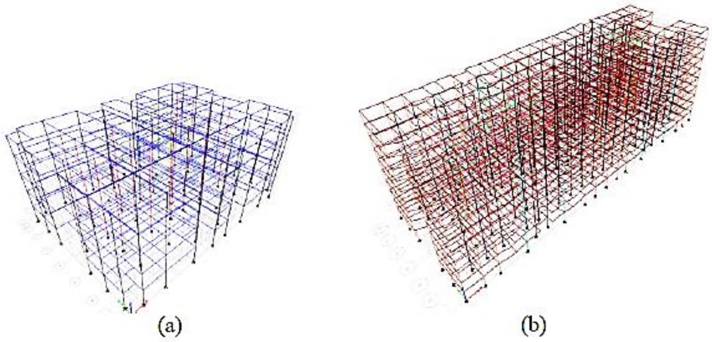


Figure 2.10: Frame Model (a) 5-Storey (b) 10-Storey (Ramli et al., 2017)

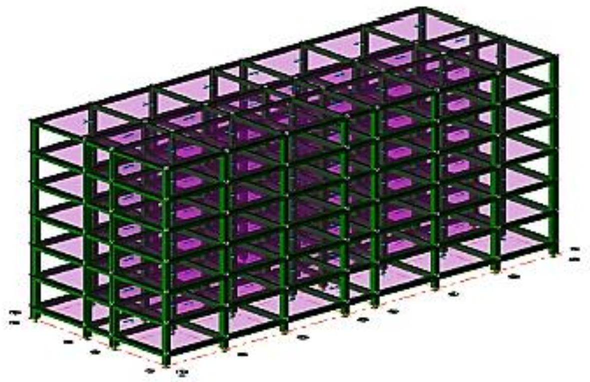


Figure 2.11: 3-D View of 6-Storey Hospital RC Building (Adiyanto et al., 2019)

2.7 Previous Researchers’ Studies on Cost Considerations for Non-Seismic and Seismic Design

Malaysia is implementing seismic design on structures to withstand the dynamic loads caused by earthquakes of small to medium magnitude. Several studies have shown increase in the material quantity (demand) and cost for reinforced concrete (RC) buildings in Malaysia for incorporating the seismic design. Past studies show that the change in percentage of concrete volume and reinforcement quantity are expected when different parameters are taken into account, such as PGA, ductility class, soil type, and building height.

2.7.1 Peak Ground Acceleration

In Malaysia, Ramli et al. (2017) compared the requirement of reinforcement for buildings with non-seismic (EC 2), and seismic (EC 8) designs with varying PGA. The behaviour factor, q of 3.9, was set to be the same for all ductility classes. This research showed that the reinforcement quantity increased with each PGA, as shown in Figure 2.12. The quantity of reinforcement of the 0.06g, 0.08g, and 0.14g structures for 5-storey buildings increased by 10.2%, 32.4%, and 33.2%, respectively, compared to non-seismic design. Similarly, for the 10-storey buildings, the quantity of steel reinforcement of the 0.06g, 0.08g, and 0.14g structures increased by 33.4%, 61.7%, and 61.8%, respectively. Therefore, a higher project cost is required for a higher value of PGA.

Ductility Class	Quantity of Reinforcement (Tonne)			Increment (%)
	Beam	Column	Total	
EC2	117.0	8.6	125.6	-
EC8 DCL0.06g	127.5	11.0	138.5	+10.2
EC8 DCM 0.08g	154.0	31.8	185.8	+32.4
EC8 DCM 0.14g	155.9	32.1	188.0	+33.2

(a)

Ductility Class	Quantity of Reinforcement (Tonne)			Increment (%)
	Beam	Column	Total	
EC2	962.3	78.7	1041.0	-
EC8 DCL0.06g	1027.8	361.0	1388.9	+33.4
EC8 DCM 0.08g	1273.9	409.4	1683.3	+61.7
EC8 DCM 0.14g	1274.3	409.5	1683.8	+61.8

(b)

Figure 2.12: Different Quantity of Reinforcement Between Non-Seismic and Seismic for (a) 5-Storey and (b) 10-Storey Buildings (Ramli et al., 2017)

Adiyanto et al. (2019) conducted a case study to estimate of steel reinforcement needed for hospital buildings in Malaysia, taking into account seismic design considerations. Four different PGA of 0.04g, 0.08g, 0.12g, and 0.16g, were used to investigate the effect of various PGA levels on the total amount of steel reinforcement. They reported that the total weight of steel reinforcement is highly influenced by PGA value, as shown in Figure 2.13. The total weight of steel per 1 m^3 concrete for buildings designed with 0.04g, 0.08g, 0.12g, and 0.16g showed to be increased in weight by 6.7 kg/m^3, 123.7 kg/m^3, 273.6 kg/m^3, and 309.1 kg/m^3, respectively, compared to non-seismic design. The authors concluded that when the behaviour factor and ductility class are constant, the steel reinforcement quantity will be significantly affected by the reference PGA. Therefore, seismically designed buildings will bear a higher material cost compared to buildings with a non-seismic design.

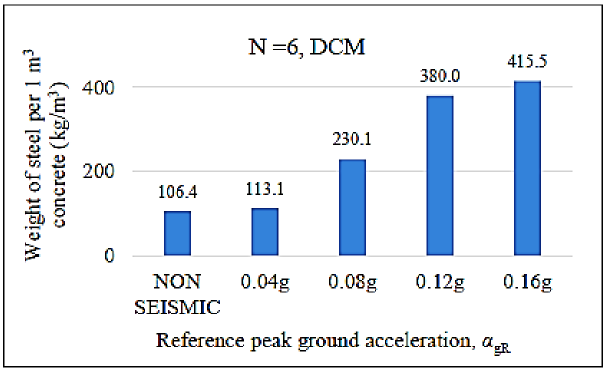
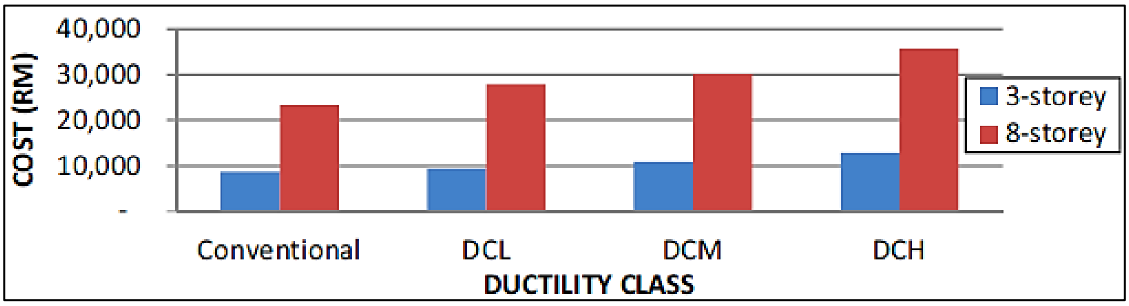


Figure 2.13: Total Weight of Steel Reinforcement for 1 m^3 Concrete for Different Values of Reference Peak Ground Acceleration (Adiyanto et al., 2019)

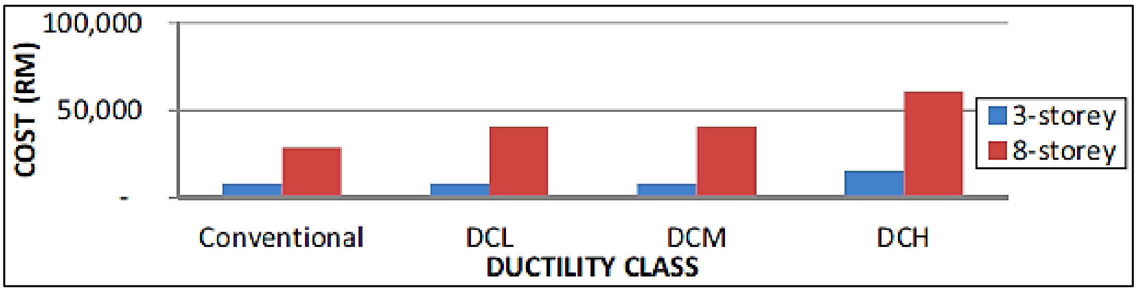
2.7.2 Ductility Class

Awaludin and Adnan (2016) performed a study to compare the difference in building material cost for non-seismic and seismic design when different ductility class was applied. The response spectrum of their study was generated using different ground accelerations, namely 0.06g (DCL), 0.20g (DCM), and 0.40g (DCH). Figure 2.14 shows that as the ductility class increases, the concrete volume and weight of steel bars also increases, leading to the increment of material cost. The total material cost of the DCL, DCM, and DCH structures for 3-storey frame structures increase by 4%, 13%, and 68%, respectively, compared to conventional structure. The DCL structure did not show a huge difference because the sizes for column and beam were not affected by the low PGA. However, higher ductility class needed more steel bars for the structure causing a huge difference in material cost for DCH structure. Similarly, for the 8-storey frame structure, the material cost of the DCL, DCM, and DCH structures increase by 33%, 36%, and

87%, respectively. There was an increase of 33% between conventional structure and DCL structure due to the increment in column and beam sizes.



(a)



(b)

Figure 2.14: (a) Cost of Steel Bar Versus Ductility Class (b) Cost of Concrete Versus Ductility Class (Awaludin and Adnan, 2016)

2.7.3 Soil Type

Recent research conducted by Roslan et al. (2019) showed the effect of different soil types on the amplification of seismic load acting on reinforced concrete buildings. There were three types of soil used to represent the variability of site conditions in Malaysia: soil type A, soil type C, and soil type E. Based on their study, the total cost of steel reinforcement for beam and column increases by implementing seismic design, as shown in Figure 2.15. The authors reported that the cost of steel reinforcement for models on soil type A increased 38%, where soil type C and soil type E increased in the range of 57% to 92% and 66% to 131%, respectively. The site condition represented by soil type influenced the increment of steel tonnage as softer ground requires a higher increment of steel tonnage than the harder ground. The findings were associated to the amplification of soil factor, the level of seismicity in the softer soil condition is higher compared to denser condition. They concluded that in order to accommodate the higher bending moment, shear force, and axial load, the model with softer soil requires a larger steel reinforcing area. As a result, the greater the area of steel reinforcement offered, the higher the cost of building material.

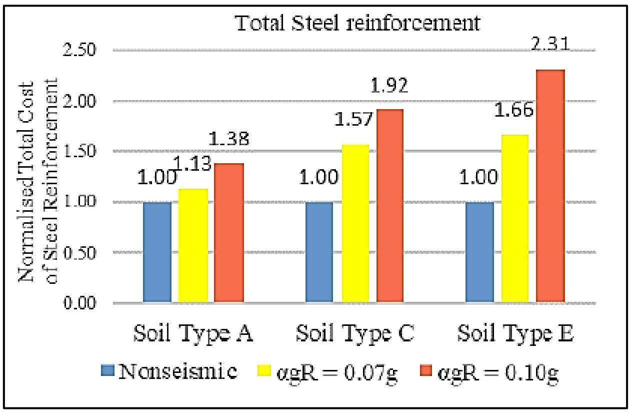


Figure 2.15: Normalized Cost of Steel Reinforcement (Roslan et al., 2019)

2.7.4 Building Height

Awaludin and Adnan (2016) and Ramli et al. (2017) investigated the influence of building height on the quantity of reinforcement for reinforced concrete buildings as shown in Table 2.3. Based on their studies, the increase of reinforcement quantity which reflects on the total material cost was in the range of 8% to 61.8%, depending on the height of structure, PGA, and ductility class being considered. As predicted, higher material cost was needed to cater for buildings with increasing number of storeys when taking into consideration the locations with varied PGA and ductility conditions.

Table 2.3: The Increment in Quantity of Reinforcement with Different Building Heights

Reference	Quantity of Reinforcement (Tonne)			
	Non-seismic	Seismic		Increment (%)
3-Storey				
Awaludin and Adnan (2016)	3.6	DCL 0.06g	3.9	8
		DCM 0.2g	4.6	28
		DCH 0.4g	5.3	47
8-Storey				
Awaludin and Adnan (2016)	9.7	DCL 0.06g	11.8	22
		DCM 0.2g	12.7	32
		DCH 0.4g	15.0	55
5-Storey				
Ramli et al. (2017)	125.6	DCL 0.06g	138.5	10.2
		DCM 0.08g	185.8	32.4
		DCM 0.14g	188.0	33.2
10-Storey				
Ramli et al. (2017)	1041.0	DCL 0.06g	1388.9	33.4
		DCM 0.08g	1683.3	61.7
		DCM 0.14g	1683.8	61.8

2.8 Summary

The review showed that the study on cost comparison between non-seismic and seismic design is relevant, especially in Malaysia. This phenomenon is particularly true with the publication of current research work in the open literature. However, inconsistency in the trend in terms of percentage increase for the cost consideration between non-seismic and seismic design was observed. In addition, most of the researchers only focused on low to medium-rise building models. Despite most of the past studies explaining that buildings incorporating seismic design showed an increase in the material cost for adopting seismic design, the results are scattered. As such, a systematic approach to address this work is required. Eventually, a broader spectrum of results that includes high-rise buildings can be achieved for the construction players to have a better judgement on material cost during budget planning.