COST EVALUATION ON THE EFFECT OF ADOPTING DIFFERENT SHEAR WALL ARRANGEMENTS FOR RECTANGULAR OFFICE BUILDING UNDER SEISMIC DESIGN

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SCHOOL OF CIVIL ENGINEERING
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by

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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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ABSTRAK

Pulau Pinang terletak di dalam zon seismik yang rendah. Walau bagaimanapun, disebabkan kejadian gempa bumi lalu yang telah menyebabkan tragedi, adalah penting untuk mempertimbangkan penglibatan reka bentuk seismik (EC8) dalam pembinaan bangunan yang hanya mematuhi reka bentuk konvensional (EC2). Kajian ini dijalankan dengan tujuan untuk menilai kesan sistem struktur yang berbeza terhadap kuantiti bahan, jumlah kos, dan keluasan lantai bersih bangunan di bawah reka bentuk seismik. Tiga jenis rangka bangunan konkrit bertetulang 25 tingkat, 30 tingkat dan 35 tingkat dengan gabungan susunan dinding ricih yang berbeza telah direka bentuk dan dianalisis menggunakan pakej perisian ETABS. Bangunan tersebut telah direka bentuk menggunakan EC2 dan MS1553:2002 masing-masing untuk beban graviti dan beban angin. Sebaliknya, EC8 telah digunakan untuk reka bentuk seismik dengan nilai rujukan Pecutan Tanah Puncak 0.05 g (kelas kemuluran rendah) dan jenis tanah D kerana ia mewakili keadaan seismik di Pulau Pinang. Keputusan menunjukkan bahawa kos keseluruhan untuk model bangunan yang berkait dengan ketinggian bangunan dan susunan dinding ricih yang berbeza telah menurun dalam julat 6.2%-16.1% untuk reka bentuk bukan seismik dan 1.1%-10.6% untuk reka bentuk seismik. Hasil dapatan ini adalah kerana penggabungan dinding ricih telah meningkatkan ketahanan bangunan terhadap beban sisi. Sebaliknya, luas lantai bersih didapati telah meningkat secara tidak ketara (1%-2%) apabila penggabungkan dengan susunan dinding ricih yang berbeza telah diadaptasi. Dapat disimpulkan bahawa penggabungan reka bentuk seismik untuk kes di Pulau Pinang telah meningkatkan jumlah kos bahan, walaupun kos tambahan boleh dianggap secara relatifnya sebagai rendah (kurang daripada 7%). Sebaliknya, penggabungan dinding ricih tambahan telah mengurangkan jumlah kos dan adalah benar untuk semua

ketinggian bangunan. Di samping itu, penggabungan dinding ricih tambahan telah meningkatkan sedikit keluasan lantai bersih dan secara khususnya adalah benar untuk kes reka bentuk bukan seismik dan seismik.

ABSTRACT

Penang Island is located in the low seismic zone. However, due to the past earthquakes incidents that caused structural damage to a few buildings to the non-seismic design, it is vital to consider the involvement of seismic design (EC8) onto the construction of building that only complied to the non-seismic design (EC2). This study is carried out with the aim to evaluate the effect of different structural systems towards the concrete volume and reinforcement bar quantity, the total cost, and the net floor area of buildings under seismic design. Three types of reinforced concrete building frame of 25 storeys, 30 storeys and 35 storeys with the incorporation of different shear wall arrangements were designed and analysed using ETABS software package. The buildings were designed using EC2 and MS1553:2002 for gravity load and wind load, respectively. On the other hand, EC8 was used for seismic design with the reference Peak Ground Acceleration value of 0.05 g (low ductility class) and soil type D as it represents the seismicity conditions in Penang Island. The results showed that the total concrete volume and reinforcement bar cost for the building models with respect to building heights and different shear wall arrangements decreased in the range of 6.2%-16.1% for non-seismic design and 1.1%-10.6% for seismic design. This finding is associated to the fact that the incorporation of shear wall increases the building resistant towards lateral load. On the other hand, the net floor area was found to be insignificantly increased (1%-2%) when the incorporation of different shear wall arrangements is adopted. It can be concluded that incorporation of seismic design for Penang case increases the total material cost, although the additional cost can be considered as relatively low (less than 7%). On the contrary, the incorporation of additional shear wall reduces the total cost (1%-11%) and particularly true for all building heights with seismic

design. In addition, the incorporation of additional shear wall slightly increases the net floor area and particularly true in the case of non-seismic and seismic design.

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LIST OF ABBREVIATIONS

DCH	Ductility Class High
DCL	Ductility Class Low
DCM	Ductility Class Medium
EC	Eurocode
IEM	Institute of Engineer Malaysia
PGA	Peak Ground Acceleration
RC	Reinforced Concrete
RCC	Reinforced Cement Concrete
RSA	Response Spectrum Analysis

LIST OF SYMBOLS

$v_{s,30}$	Average Shear Wave Velocity
q	Behaviour Factors
γ_I	Importance Factor

CHAPTER 1

INTRODUCTION

1.1 Background

Earthquakes are a frequent event that can strike without warning and cause significant damage to engineered buildings and structures. Although it is difficult to prevent earthquakes, the danger can be reduced by using seismic designs. Due to a number of variables, including tectonic plate movement, unexpected fault slips, and volcanic eruptions, earthquakes cannot be forecast with precision. An engineer's job in structural engineering is to achieve the highest level of building structure safety while minimising construction expenses.

Malaysia is bordered by an active seismic zone for at least 350 kilometres away and underlain by a tectonically stable crust, Sunda Plate. This condition gives the perception that Malaysia is earthquake-free. Thus, it is justified to assume that Peninsular Malaysia is positive toward seismic risk under these circumstances (Gill et al., 2015). However, some parts of Malaysia experienced the tremors from long distance and local earthquake such as Penang Island and Sabah, respectively. Figure 1.1 shows the location of Malaysia on the Sunda Plate and Tectonic Plates Surrounded Malaysia (Loi et al., 2018).

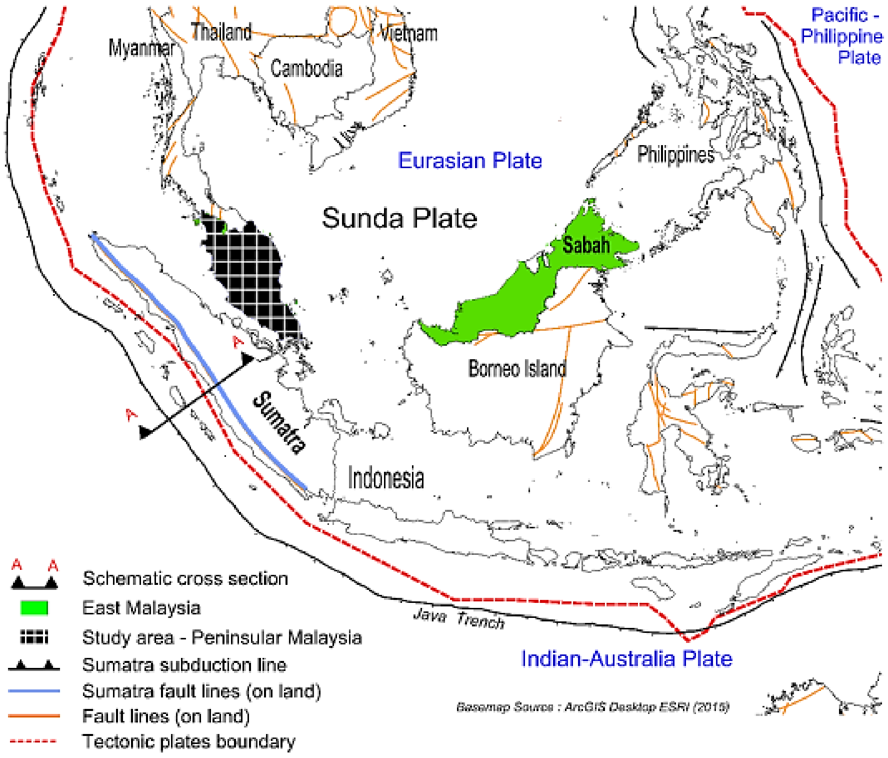


Figure 1.1: Location of Malaysia on the Sunda Plate and Tectonic Plates Surrounded Malaysia (Loi et al., 2018)

In high-rise building, structural systems play a vital role in resisting the gravity as well as lateral load. The accumulation of the gravity load to the foundation and the magnitude of the lateral load will be increase following the increase in number of storeys (Chandiwala, 2012). In order to resist the lateral load acting on high-rise buildings efficiently, several special structural systems can be introduced such as moment resistant frames, braced frames, shear wall structures and tube structures. Various structural systems can be adopted into the design of high-rise buildings to obtain the most economical structure in terms of the main structural materials cost that is able to fulfill the non-seismic and seismic design requirements. Table 1.1 shows the description of the structural forms that are suitable for high-rise building.

Table 1.1: Description of Structural Forms

Structural System	**Description**
Rigid/ Moment Resistant Frame	• Consists of beam and column connected by rigid or semi rigid joints.
Braced Frames	• Truss members are added in the form of Cross-bracing, V-bracing, or K-bracing at the outer perimeter improve the efficiency of pure rigid frame.
Shear Wall Structures	• Continuous reinforced concrete vertical wall which extends over the full height of the building • Light weight and high in-plane stiffness and strength. • Easiest and effective lateral load resisting systems.
Tube Structures	• Incorporation of closely spaced column at the perimeter of the high-rise building. • The building behaves equivalent hollow tube. • Capable to resisting lateral forces from any direction

1.2 Problem Statement

Almost all high-rise buildings in Malaysia have been designed without considering seismic load. With the published Malaysian National Annex to Eurocode 8, the incorporation of seismic load in the design of high-rise buildings may need to be considered in the near future. However, Malaysia has limited experience in dealing with seismic design and there are many areas that need to be explored such as the study on the structural system such as the increase in material cost and the effect on the net floor area. Examples of the common structural system are wall-frame, shear wall and tube structures. In the case of wall-frame structural system, the location of the shear walls, and the cross-sectional area of the reinforced concrete columns and shear walls will govern the design. However, the difference in the main material cost between non-seismic and seismic design for adopting wall-frame structure is still lacking in the open literature. In general, the use of more structural walls enhances the strength capacity and generally increases the cost and reduces the net floor area. However, the increase in cost can be compensated by reducing other structural member sizes and reinforcement. In addition, the reduction of column size may be able to compensate the loss of floor area due to the presence of additional wall. This possibility needs to be investigated in order to provide useful information to the construction players for preparing accurate budgeting for construction and setting profitable selling/renting prices of the properties.

1.3 Objectives

The objectives of the study are:

1. To compare the material cost of the main structural members under non-seismic and seismic design considerations for incorporating additional shear walls.

2. To evaluate the effect of incorporating additional shear on the net floor area.

1.4 Scope of Work

The scope of work involves the modelling, analysis, and design of rectangular office building models with different heights. The general scope are stated as below:

- The dimension of the floor plan for the rectangular office building is set to be 99 m x 27 m following the building data provided by The Institution of Engineers Malaysia (IEM), Penang Branch.
- The design is based on Eurocode 2 for reinforced concrete design and Eurocode 8 for seismic design.
- The analysis and design of the building models are performed with the aid of ETABS software package.
- There are many types of structural forms that can be adopted for resisting lateral load, but this study will only incorporate additional shear wall to the existing wall-frame building model.

- This study only covers building with different locations of structural shear wall on soil type D.
- The quantity and cost of the materials only focus on the main frame members namely, on beams, columns, and RC walls for both non-seismic and seismic design considerations.
- The total cost is calculated based on the design demand of the two main construction materials namely, concrete volume and the weight of steel reinforcement.

1.5 Significance of Study

This study provides information on the cost comparison of the main frame of high rise building subjected to non-seismic and seismic load. In addition, the information pertaining to the changes of the net floor area (that can influence the selling or renting price) due to the size and arrangement of the shear walls are also investigated. The results from this study will broaden the spectrum of the cost analysis data that are currently available in the open literature. Therefore, this study contributes towards a better understanding to the design engineer for selecting and optimize the design concept especially when considering lateral loads, and to the construction players especially for preparing the construction budget and setting an accurate selling cost of a property.

1.6 Dissertation Outline

This thesis dissertation contains 5 chapters and the description for every chapter is as follows:

Chapter 1 discusses the background, problem statement, objectives, scope of works and significance of study of the research topic.

Chapter 2 reviews the design requirement pertaining to seismic design. Discussions on the factors affecting the damage of structure due to seismic force, and description of several typical structure systems are highlighted. In addition, this chapter also reviews the past research works pertaining to the comparison of building design subjected to non-seismic and seismic loads.

Chapter 3 describes the overall procedures for conducting the analyses and design of the buildings subjected to lateral loads. The description of the models, building data, loading intensities, load combination and the essential steps involved for using ETABS 2018 software are also presented in this chapter.

Chapter 4 presents the results pertaining to of the incorporation of the shear wall at different locations of the building models. The discussions also cover the overall cost of the building main frame and the net floor area.

Chapter 5 summarizes the important findings of this research based on the objectives of the study before the conclusion can be made. To further appreciate the study on incorporation of shear wall in buildings, recommendations for the work in the future are listed.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter provides information on the seismic activity in Malaysia as well as the causes of structural damage during earthquakes. Additionally, the seismic design approach for reinforced concrete buildings employing Malaysia National Annex and Eurocode 8 is described. The economic issues for seismic and non-seismic design as well as past research studies are also reviewed in this chapter.

2.2 Seismic Activities in Malaysia

East Malaysia's tectonic plate is between the Philippine Sea Plate and the Eurasian plate, while Peninsular Malaysia is between Australia and Eurasian plates. Despite Malaysia's location on the dormant Sunda Plate and low seismicity zone, tremors from nearby nations like Indonesia as well as earthquakes of local origin can still be felt. Malaysia is generally outside the Ring of Fire as shown in Figure 2.1. The red spots along the tectonic plate borders are representing the active volcanoes.

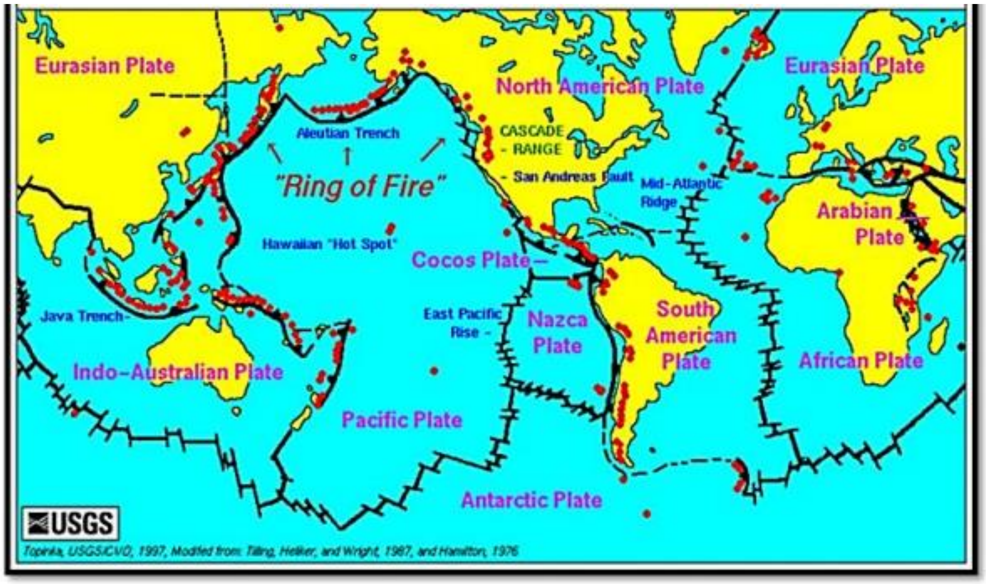


Figure 2.1 : Location of active volcanoes, Plate tectonics and Ring of Fire (USGS, 2019)

One of the most significant regional earthquakes that brought catastrophic impacts was the 2004 Indian-Ocean Earthquake with a magnitude of Mw 9.1. This catastrophic earthquake event triggered the devastating tsunami and killed 68 lives in Malaysia (Komoo and Mazlan, 2005). Other than deaths and destructions, this earthquake had also disturbed and distorted the surrounding plate. The whole of the Peninsular was moved toward the west and southwest, resulting in both co-seismic and post-seismic deformations for the whole of Southeast Asia. Peninsular Malaysia has undergone the most severe deformation and will therefore be more affected by future earthquakes because it is now closer to the epicentre (Mohd Omar, 2014). Figure 2.2 shows the earthquake-prone region of Malaysia.

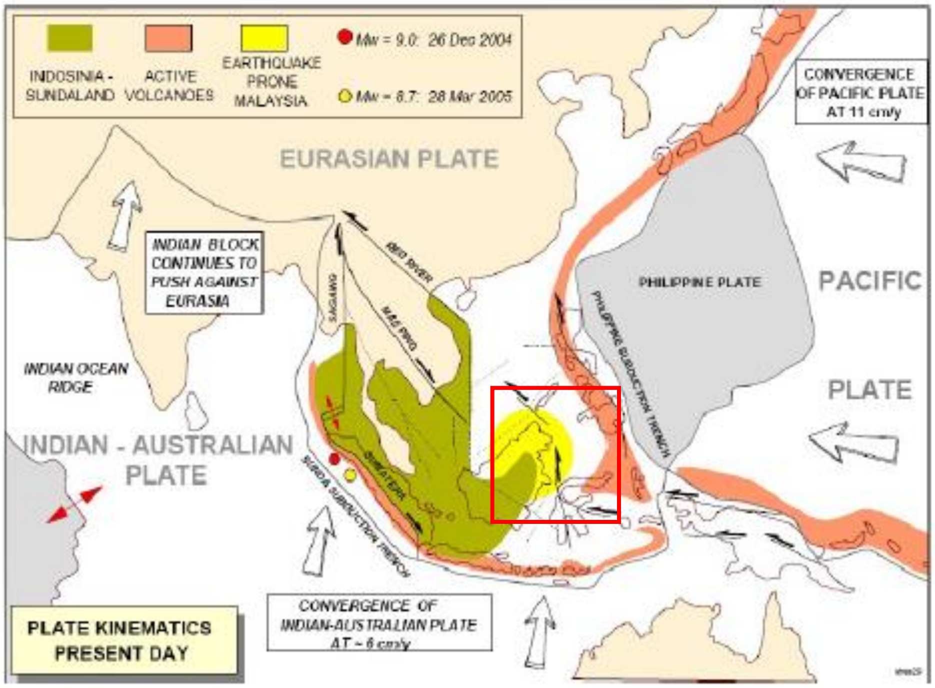


Figure 2.2: Earthquake-prone region of Malaysia (Tjia, 2010)

2.3 Factors Affecting the Structural Damage of Structures due to Earthquake Events

Earthquake can cause damage to the structural elements causing failures to buildings. There are several factors that lead to this disaster during earthquake events. The following subsections examine the factors that can cause damage or failure to a structure.

2.3.1 Soft Storeys Mechanism

A soft storeys mechanism forms in a structural system if the intensity of the ground motion increases above a particular point. If the infill walls are used and the overall ductility capacity of the frames is poor, the collapse is likely to happen during an earthquake event (Demirel et al., 2022) as shown in Figure 2.3.

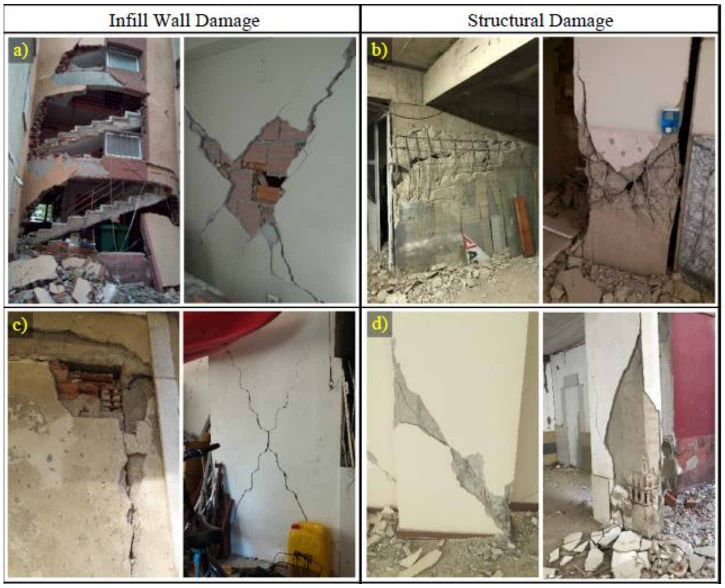


Figure 2.3: Structural and infill wall damage in Bayrakli, Turkey
(Demirel et al., 2022)

2.3.2 Ductility Class

The ductility classes define the allowable remaining deformation in structural elements, which ultimately is associated with the energy dissipation capacity that minimizes the structural reaction due to seismic (Awaludin and Adnan, 2016).

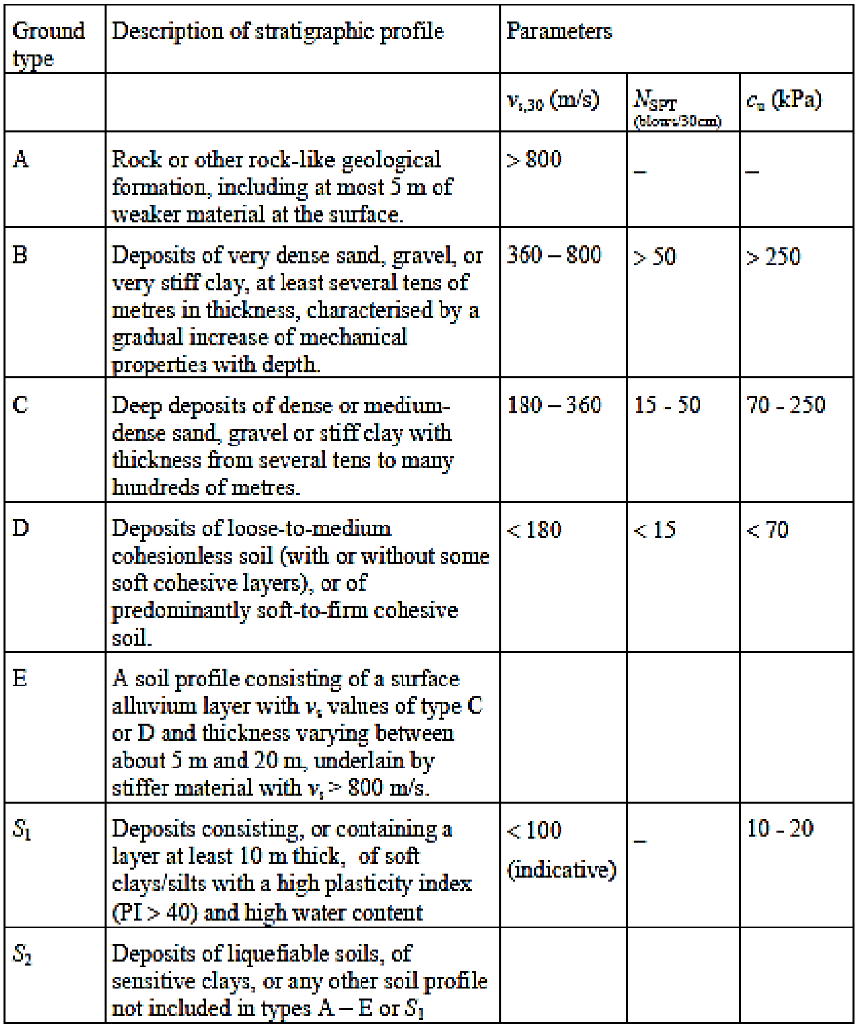
For reinforced concrete buildings, three ductility classes are introduced, namely:

1. Ductility Class L (DCL) refers to a structure designed under Eurocode 2 and only lightly supplemented by a few additional detailing rules to enhance the ductility.
2. Ductility Class M (DCM) refers to structures designed to enable the structure to enter within the inelastic range without brittle failure.
3. Ductility Class H (DCH) refers to structures designed to have stable mechanisms associated with large hysteretic energy dissipation.

2.3.3 Soil Type

Seven different ground types, namely: A, B, C, D, E, S1 and S2 are included in Eurocode 8 for soil sediments with a depth of less than or equal to 30 metres. In contrast, the Malaysia National Annex only considers the five ground categories A, B, C, D, and E for soil deposits deeper than 30 m. The ground type classification scheme is shown in Table 2.1 and Table 2.2 are based on Table 3.1 of Eurocode 8 and Table A1 of the Malaysia National Annex.

Table 2.1: Ground type classification (Table 3.1, MS EN 1998-1:2015)



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			

Based on Table 2.1, $v_{s,30}$ is define as the average shear wave velocity, and computed in accordance with the following expression:

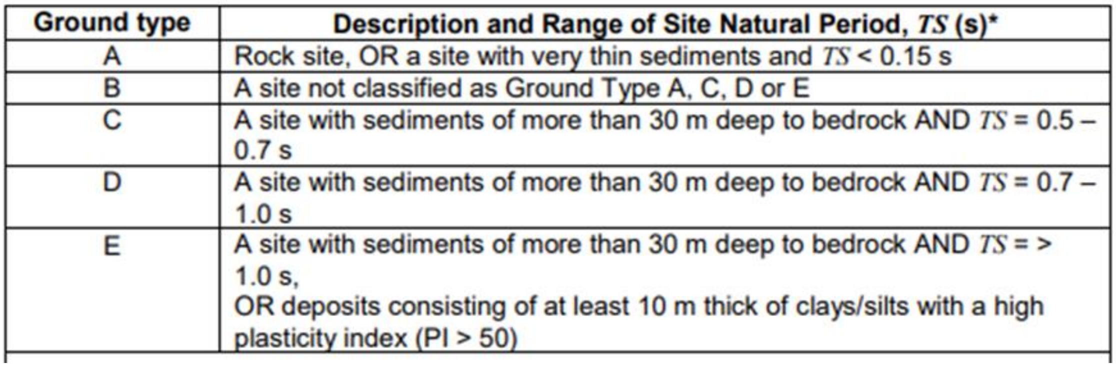
$$V_{S,30} = \frac{30}{\sum_{i}^{n} \frac{h_i}{V_i}} \qquad (2.1)$$

where:

h_i = Thickness of soil layer

V_i = Shear-wave velocity (at a shear strain level of 10 – 5 or less) of the *i-th* formation or layer, in a total of N, existing in the top 30m

Table 2.2: Ground type classification (Table A1, Malaysia NA to MS EN 1998-1:2015)



Ground type	Description and Range of Site Natural Period, *TS* (s)*
A	Rock site, OR a site with very thin sediments and *TS* < 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 *TS* = 0.5 – 0.7 s
D	A site with sediments of more than 30 m deep to bedrock AND *TS* = 0.7 – 1.0 s
E	A site with sediments of more than 30 m deep to bedrock AND *TS* = > 1.0 s, OR deposits consisting of at least 10 m thick of clays/silts with a high plasticity index (PI > 50)

Hong et al. (2020) stated that building's seismic performance is affected by different soil type, where the foundation soils play the vital role in the proper seismic design of structures. In their study, building models under soil type D and E exhibited the highest seismic base shear force in the form of lateral load. Therefore, the material cost will increase significantly under soil type D and E due to the use of larger structural elements in a building in order to meet the seismic design requirements.

2.4 Wall Frame System

Wall frame system is a combination of shear walls with rigid frame structure to resist the horizontal loading as shown in Figure 2.4. The walls which tend to deflect in a flexural configuration, and the frames which tend to deflect in a shear mode are constrained to adopt a common deflected shape by the horizontal rigidity of the girders and slabs (refer to Figure 2.5). As a result, the walls and frames interact horizontally to produce a stiffer and stronger structure.

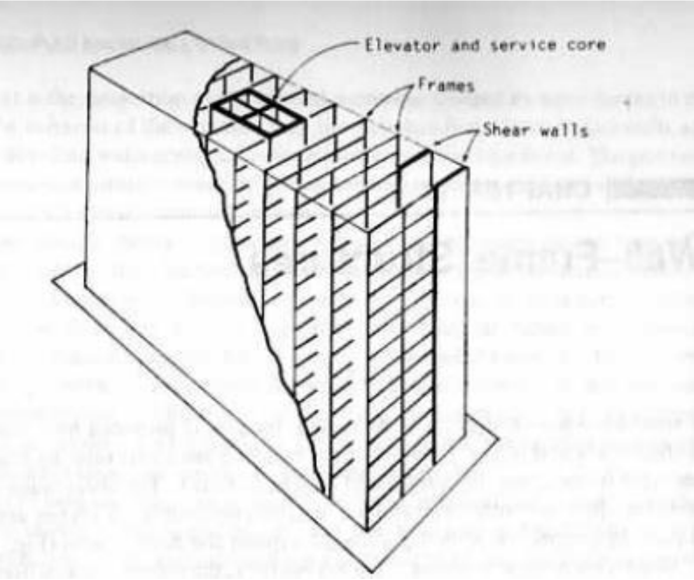


Figure 2.4: The representative of wall-frame structure. (Smith, 1991)

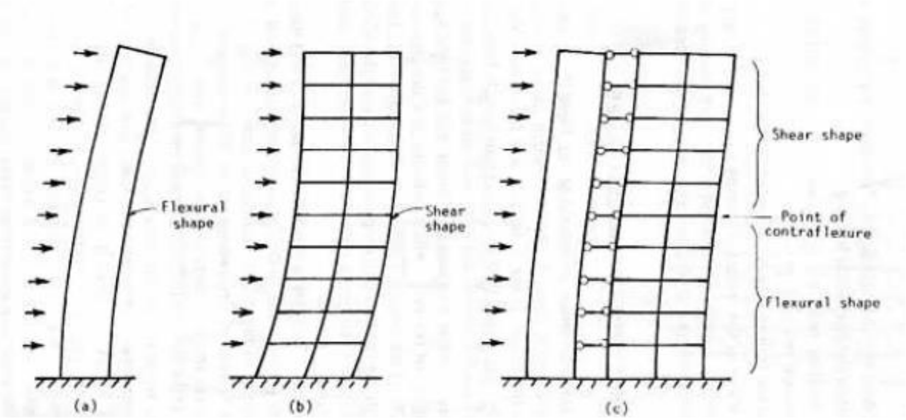


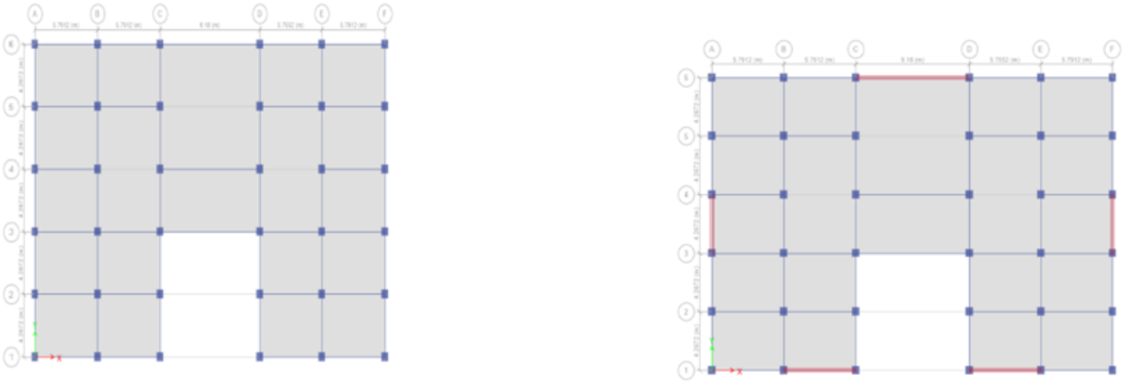
Figure 2.5: (a) Wall (b) frame (c) wall-frame structure subjected to horizontal loading (Smith, 1991)

The potential advantage of adopting this system depends on the amount of horizontal interaction which is governed by the relative stiffness of the walls and frames, and the height of the structure. The taller the building, the stiffer the frames and the greater the interaction. In low rise buildings, the contribution of the frame to the lateral resistance is often negligible, but in medium-to high rise buildings, the lateral loading can be significant and should be considered in the design for lateral loadings. The common practice of this system in design of high-rise structures is assumed that the shear walls or cores resisted the lateral loading, and the frames resisted the gravity loading only (Smith et al., 1991).

2.5 Model Analysis

Prior to the analysis work, buildings are normally modelled with the aid of commercial software package. Generally, it can be performed using either a two-dimensional (2-D) or three-dimensional (3-D) model, based on the required computational time and level of precision. However, in the case where translational and rotational movement in all directions are taken into account, 3-D modelling typically offers a more realistic analysis. Nowadays, there are many commercial software that have the capability to perform seismic analysis and design such as ETABS, TEKLA Structural Designer and STAADPRO V8i. In addition, ETABS and TEKLA software has the advantage of producing drawings and material taking-off.

Krishnamurthy et al. (2022) conducted a study using 4 models of 10-storey reinforced cement concrete (RCC) building with bare frame and shear wall using ETABS software. The frame models used for the design and analysis are shown in Figure 2.6. In addition, Adiyanto et al. (2019)modelled 6-storey building using a three-dimensional (3-D) approach, generated using Tekla Structural Designer software, as shown in Figure 2.7.



(a) (b)

Figure 2.6: Plan view of the models with (a) bare frame (b) shear wall (Krishnamurthy et al. (2022)

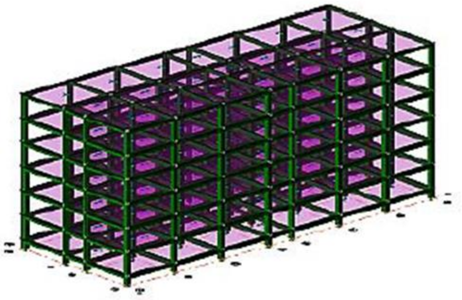


Figure 2.7: 3-D view of 6-storeys hospital RC building (Adiyanto et al., 2019)

2.6 Previous Case Study on Non-Seismic and Seismic Design

Several studies have shown that the incorporation of seismic design increase the material quantity and cost for RC buildings in Malaysia. In addition, the discussions pertaining to the percentage difference in terms of the material quantity with different parameters, namely, ductility class, peak ground acceleration, soil type, and building height are also presented. Besides, the past research on structural system adopted in seismic design are reviewed and discussed accordingly.

2.6.1 Ductility Class

Awaludin and Adnan (2016) conducted a study to compare the difference in terms of material cost between the non-seismic and seismic design of buildings by varying the ductility classes and building height. Three different ground accelerations, namely 0.06g (DCL), 0.2g (DCM) and 0.4g (DCH) were investigated. In terms of structural system, the study only considered reinforced concrete moment-resisting frame. Figure 2.8 and Figure 2.9 show the percentage increase in terms of steel tonnage and concrete volume, respectively. In the case of the 3-storey buildings, the total percentage increase material cost of the DCL, DCM and DCH buildings were reported to be 4%, 13% and 68%, respectively compared to the non-seismic design. The authors also reported that the DCL and DCM building did not show significant increase in the volume of concrete and steel reinforcement. On the other hand, the DCH building required large amount of steel for the building due to the high ductility level detailing requirements as stated in Eurocode 8. In the case of the 8-storey buildings, the increase in terms of the total material cost of the DCL, DCM and DCH buildings were calculated to be 33%, 36% and 87%, respectively.

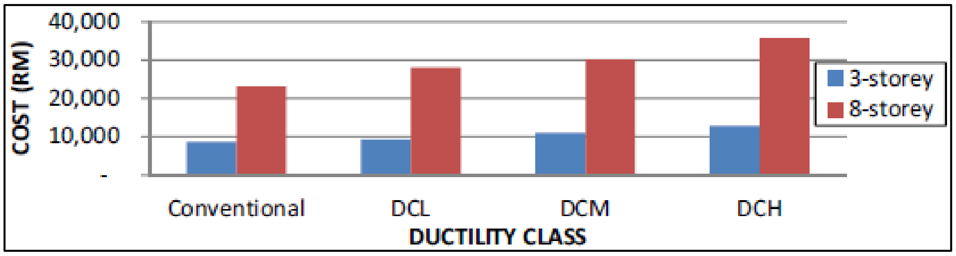


Figure 2.8: Cost of Steel Bar Versus Ductility Class
(Awaludin and Adnan, 2016)

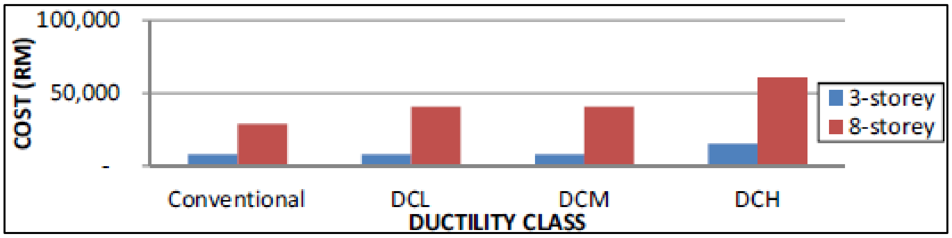
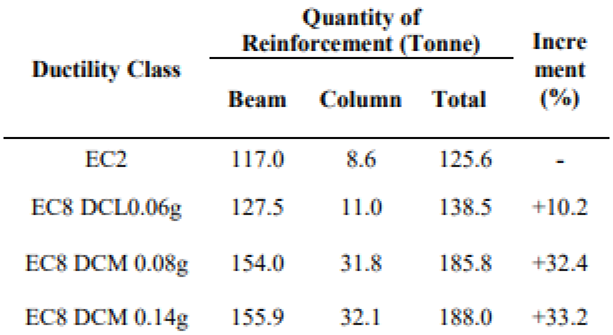


Figure 2.9: Cost of Concrete Volume Versus Ductility Class
(Awaludin and Adnan, 2016)

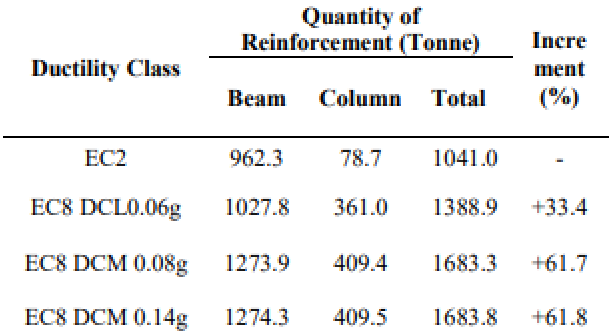
2.6.2 Peak Ground Acceleration

Ramli et al. (2017) compared the design requirement for buildings subjected to EC2 and EC8 with varying the Peak Ground Acceleration (PGA) values. The buildings were modelled as rigid moment-resisting frame. The results showed that the reinforcement quantity increased with respect to the PGA values, as shown in Figure 2.10 and Figure 2.11. The increase in the reinforcement quantity for the 0.06g, 0.08g and 0.14g for 5-storey buildings was reported to be 10.2%, 32.4% and 33.2%, respectively. Similarly, for the 10-storey building the increase in the reinforcement quantity for the 0.06g, 0.08g and 0.14g was quantified to be 33.4%, 61.7% and 61.8%, respectively. The authors concluded that, the adoption of high PGA was significantly affecting the reinforcement quantity with respect to the building height.



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

Figure 2.10: Different quantity of reinforcement between non-seismic and seismic for 5-storey buildings (Ramli et al., 2017)



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

Figure 2.11: Different quantity of reinforcement between non-seismic and seismic for 10-storey buildings (Ramli et al., 2017)

Adiyanto et al. (2014) evaluated the cost comparisons of low-rise building models with varying levels of reference PGA, that approximated the Malaysian seismic zone. The scope of study included the investigation on the effect of the behaviour factors, *q* in terms of the normalized cost of the main building frame. The authors found that, the higher the PGA value, the higher the normalized cost and particularly true for both behaviour factors as shown in Figure 2.12. These findings were associated to the increase in the spectral acceleration and base shear as a result of increasing the PGA. However, it is worth mentioning that the behaviour factor, *q* will not affect the total volume of concrete used for the design.

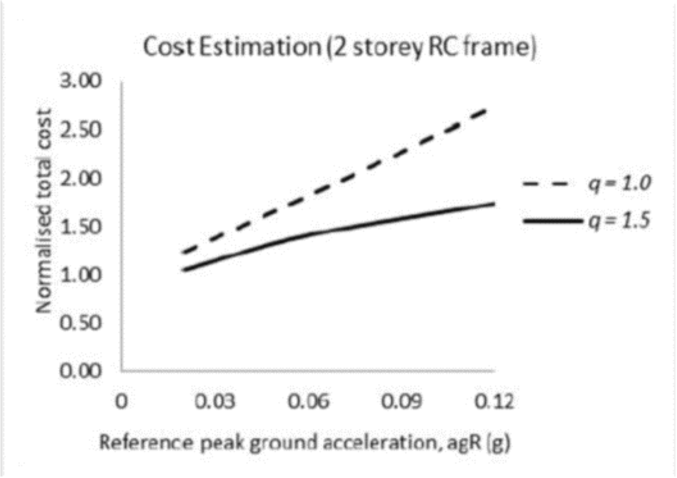
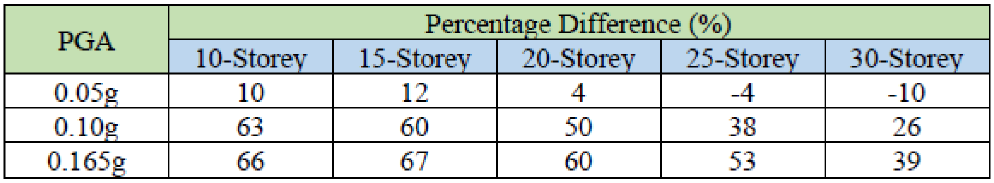


Figure 2.12: Estimated Cost Normalized to Current Practice without Seismic Design (Adiyanto et al., 2014)

Lim (2021) evaluated cost considerations for reinforced concrete office building in Malaysia incorporating seismic design varying the PGA values of 0.05g, 0.10g, and 0.165g to represents the seismicity conditions that are found in Peninsular, Sarawak and Sabah. The author reported that building models incorporating seismic design showed increments in concrete and reinforcement requirements compared to non-seismic design. In addition, the author reported 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 (refer Table 2.3) . The author found that this finding is due to the wind load acting on high-rise buildings becomes more critical and particularly true for low seismicity level with PGA 0.05g.

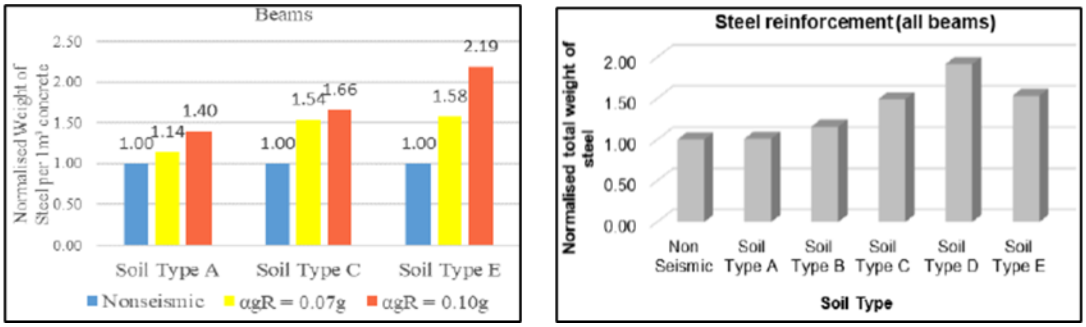
Table 2.3: Percentage difference in terms of total material cost between non-seismic and seismic design at different at different PGA and building heights



PGA	Percentage Difference (%)				
	10-Storey	15-Storey	20-Storey	25-Storey	30-Storey
0.05g	10	12	4	-4	-10
0.10g	63	60	50	38	26
0.165g	66	67	60	53	39

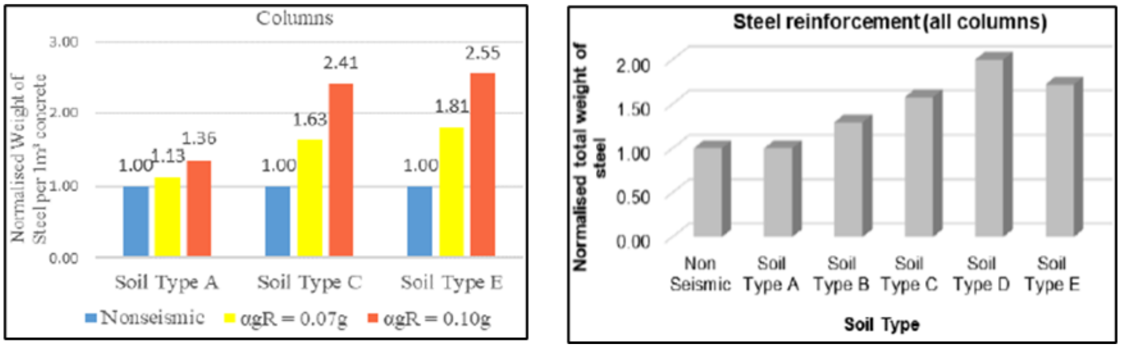
2.6.3 Soil Type

Roslan et al. (2019) and Mustafa et al. (2019) investigated the effect of different soil types on the application of seismic load acting on reinforced concrete buildings. Based on their studies, as shown in Figure 2.13 and Figure 2.14, the cost of steel reinforcement for beam and column showed an increase in the normalized steel reinforcement quantity under the seismic design and particularly true for buildings on soft soil. The level of seismicity in the softer soil condition is amplified by higher soil factor that leads to higher seismic force. The authors concluded that buildings located on a softer soil are required to withstand higher bending moment, axial load and shear force, leading to high material cost in steel reinforcement compared to building on hard soil.



(a) (b)

Figure 2.13: Effect of soil type on normalized weight of steel reinforcement for all beams
(a) Roslan et.al, (2019) (b) Mustafa et al, (2019)



(a) (b)

Figure 2.14: Effect of soil type on normalized weight of steel reinforcement for all columns
(a) Roslan et al, (2019) (b) Mustafa et al, (2019)

Toh (2021) conducted a cost comparison for non-seismic and seismic design of a rectangular building structure located on different soil types based on Malaysian Annex to Eurocode 8. The author generated five types of RC building frames with different storey height, namely, 10 storeys, 15 storeys, 20 storeys, 25 storeys, and 30 storeys with the aid of ETABS software package. The author performed the analysis using PGA of 0.06g.

Based on the Figure 2.15, the authors reported that the overall cost for building models situated on soil type A and subjected to seismic load decreased in the range of 3%-

13% compared to non-seismic design. Soil Type D showed an increased in the percentage difference (2%-15%) from 10 storeys to 25 storeys. The percentage difference of cost of materials reduced by 2% for 30 storeys. Besides, soil type E showed an increased in the percentage difference (0%-8%) from 10 storeys to 20 storeys. The percentage difference of cost of materials reduced by 3%-7% after 20 storeys. The author concluded that soil type D showed the highest increase in cost compared to non-seismic design due to the high value of base shear force and spectral acceleration at the fundamental period. Similar study can also be seen in the work of Chan (2021).

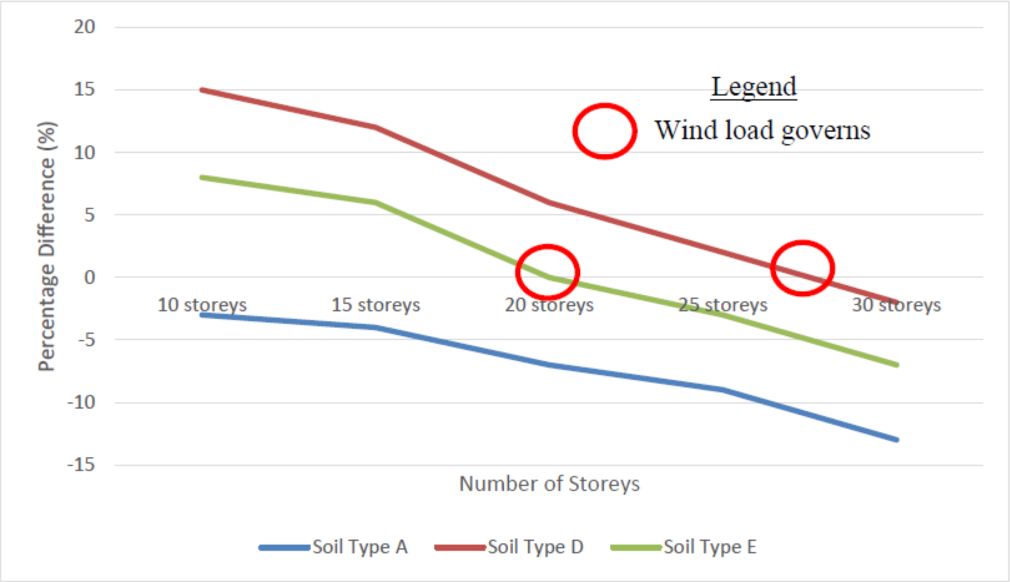


Figure 2.15: Graph of percentage difference in the material cost of seismic design compared to non-seismic design (Toh, 2021)

2.6.4 Building Height

According to Ramli et al. (2017) the building height is affecting the quantity of reinforcement and cost increase in the seismic design of RC buildings. The authors modelled two residential building models with 5 and 10 storeys heights by using frame system as the structural system. Based on their findings, the increase of the reinforcement quantity in term of the material cost was reported to be in the range of 10.2%- 33.2% and 33.4%-61.8% for the 5 and 10 storeys, respectively compared to the non-seismic design. In addition, Awaludin and Adnan (2016) modelled 3 storeys and 8 storeys building structure using STAAD.Pro to investigate the cost implementation on earthquake resistance design. The authors found that the increase in the reinforcement quantity for the 3 and 8 storeys were in the range of 8%-47% and 22%-55%, respectively compared to the non-seismic design. Therefore, taking into account the ductility values as well as the seismic design, a higher material cost was required to accommodate buildings with an increasing number of storeys.

2.6.5 Structural System

Ahamad and Pratap (2020) modelled a 20 storeys RC building to investigate the ideal location of shear walls building under different seismic zones using ETABS 2015. Three models were developed, namely, building without shear wall, shear wall at one end and shear wall at four ends respectively. Based on Figure 2.16, the authors reported that building with shear wall at one end (Case B) and shear wall at four ends (Case C) exhibited the lesser storey displacement in the *x* and *y* direction under different seismic zone compared to the building without any shear wall (Case A) for seismic zone V. The percentage difference was reported to be -28.44% and -39.69% for case B and case C, respectively compared to case