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The Effect of Seismic Design on Total Cost of Structural Work for Medium Rise Apartment Building

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Abstract. People believed Malaysia did not experience earthquakes because the country is not in the Pacific Ring of Fire. Then, an earthquake of magnitude M_w 6.0 struck Ranau, Sabah, meaning Malaysia was no longer safe from seismic catastrophes. This is especially true when most buildings in Malaysia are not made to withstand the shaking that comes from earthquakes. Considering the seismic design will mean using higher steel reinforcement, immediately raising costs. Hence, this paper studies the cost effect on Sabah's 6-story reinforced concrete (RC) apartment building. The study had three levels of reference peak ground acceleration: α_{gR} = 0.08 g, 0.12 g, and 0.16 g, and the soil type was D which was classified as Ductility Class Medium (DCM). In the comparison between the non-seismic and seismic models, the findings suggested that the amount of steel reinforcement per 1 m^3 of concrete increased by 7% and 31%, respectively. Other than that, the cost increment of structural work increased by 3.3% to 12.7% compared to the non-seismic model.

Keywords: 6-story RC building, estimation total cost, seismic design, structural works.

1. Introduction

Earthquakes are spontaneous movements on the surface of the Earth due to the sudden release of strain built up on faults over many decades. These movements have a significant impact, which can cause people to die and buildings to fall [1]. Geography and topography make tsunamis, earthquakes, and volcanic eruptions more likely to happen [2]. The Pacific Ring of Fire (RoF) exposes the Pacific Ocean's margins to intense earthquakes and volcanic eruptions regularly [3]. Generally, Malaysia consists of two mainlands. Peninsular Malaysia and East Malaysia are the two mainlands on the island of Borneo. East Malaysia comprises two states: Sabah and Sarawak [4]. People had the misconception that Malaysia did not suffer from aftershocks because the nation is not located within the Pacific RoF [5]. This Pacific RoF predominantly affects Indonesia and the Philippines [4]. Then, a magnitude, M_w 6.0 earthquake hit Ranau, Sabah. That earthquake was recognized as Malaysia's most significant local fault after the magnitude, M_w 5.8 earthquake in Lahad Datu in 1976. This showed that Malaysia was no longer safe from earthquakes [5]. It is conceivable that earthquakes of this magnitude will not cause widespread devastation; however, they will still cause some damage to the structures that they strike. This is important because most buildings in Malaysia do not withstand shaking from an earthquake [6].

A reconnaissance team recorded damage to reinforced concrete (RC) structures built without earthquake provisions. The damage was particularly severe on beams, columns, and joints on beams - columns [5]. These damages were due to the impact of Weak Columns - Strong Beams [7]. The event also caused extensive damage to non-structural components of buildings; brick walls, and ceilings [7, 8]. The shear failure on the X-mark diagonal crack in the brick walls was proven to have damaged the non-structural members [9]. Since the design of the structures was not seismically sound, the event caused damage to the 61 buildings, which included a mosque, schools, and a hospital [10].

Implementing the seismic design is necessary to lessen the damage caused to buildings, particularly in Sabah, which was regarded as a seismic region with moderate activity [4, 11]. Incorporating the results of the seismic design requires a higher amount of steel reinforcement, which also drives up costs. However, considering the seismic design, the repair and maintenance prices will decrease, bringing future benefits [12]. Several studies have been done to determine the increase in the cost of construction materials due to the influence of earthquake provisions on various characteristics. Past researchers concluded that if the earthquake provision were to be adopted, a higher amount of steel reinforcement would increase the expense of construction materials at a higher rate [4, 7, 8, 12]. Therefore, this research aims to study the effect of total cost with the influence of reference peak ground acceleration (PGA), α_{gR} and soil type of RC apartment building in Sabah, with consideration of ductility class medium (DCM) design as suggested by the Malaysia National Annex [13].

2. Methods

Most past researched were only related to the low-rise building with seismic design considerations influencing the cost of implementing soil factor, S, as suggested by the National Annex [13] and Eurocode 8 [14]. The research focused on low-rise buildings made of reinforced concrete (RC). The research studied several soil types, S, and seismicity levels, α_{gR}. Past researchers agreed that a seismic design increased the expense of steel reinforcement and construction materials [4, 7, 12, 21].

Previous reseached [21] highlighted in their paper the consideration of seismic design influencing the materials' cost. This research focused on the general two-story hostel building made of reinforced concrete. This research had studied four soil types (B, C, D, and E) and five seismicity levels; the reference peak ground acceleration values, α_{gR}, were 0.04g, 0.06g, 0.07g, 0.12g, and 0.16g. This study was divided into three phases: model generation using Tekla Structural Designer 2019 software, structural and seismic design analysis, and the taking-off process. The results showed that the cost of the structural work for the two-story RC building increased by approximately 1% to 12%, depending on the type of soil and seismicity level [21].

However, there is a limited study in medium-rise buildings that implement the seismic design. Therefore, this paper focuses on a medium-rise building in Sabah that implements the seismic design. This section will describe the measures taken in conducting this research. The 6-story apartment building made of RC served as the premise for this research's selection model. This section investigates the effect of PGA, α_{gR} = 0.08 g, 0.12 g, and 0.16 g and soil type, precisely Soil Type D, on the amount of steel reinforcement that will impact the total cost. In this study, Tekla Structural Designer 2021 was used for the analysis. The main guides for modelling the RC apartment building were Eurocode 8 [14] and the Malaysia National Annex to Eurocode 8 [13].

2.1. Model Design

A typical key plan for a medium-rise RC apartment building was created and used as a model during the initial phase. The latter was 6-story tall, signifying Malaysia's medium-rise RC buildings. The moment-resisting multi-bay frame system was evaluated as a structural design with added shear walls and a lift core. Using Eurocode 2 [15] to represent current construction industry practices in Malaysia, the fundamental model was designed without seismic consideration. Then, the take-off process involved measuring the overall concrete volume and steel reinforcement weight for the basic model. The data from Phase 1 was referred to as controls for Phases 2 and 3. Tables 1–3 show the beams, columns, and

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shear walls cross sections. Meanwhile, Figure 1 shows the view of a 6-story apartment building in Sabah designed for this study. Meanwhile, Table 4 shows the size of reinforcement used in this research.

Table 1. Cross section for beams

Beams	Dimension (mm)
Beams	(250 x 500) mm, (300 x 300) mm, (300 x 500) mm, (300 x 700) mm
Water Tank Beams	(300 x 700) mm, (350 x 800) mm

Table 2. Cross section for columns

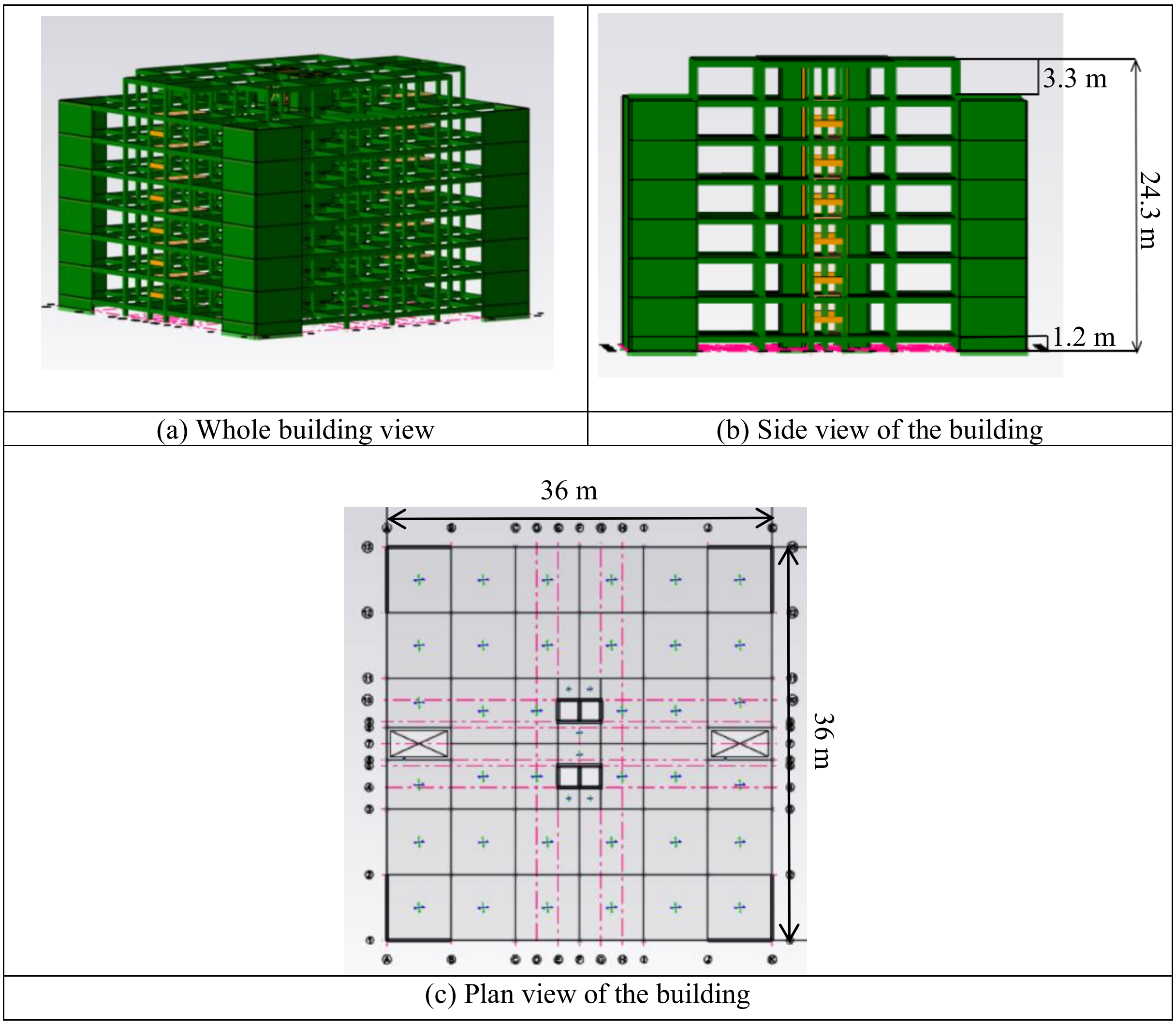
Columns	Dimension (mm)
C1	(400 x 400) mm
C2	(450 x 450) mm

Table 3. Cross section for walls

Walls	Thickness (mm)
Lift Core	300 mm
Shear Walls	300 mm

Table 4. The size of reinforcement soil type for each model

Element	Component	Type (Diameter)
Beams	Link	H8
	Flexural Reinforcement	H12 H16 H20 H25
Columns	Link	H8
	Flexural Reinforcement	H16 H20 H25 H32
Walls	Link	H10 H12
	Flexural Reinforcement	H16 H20
Slabs	Loose Bar	H6 H8



(a) Whole building view (b) Side view of the building

(c) Plan view of the building

Figure 1. View of the 6-story apartment building in Sabah

2.2. Seismic Design Analysis

In this phase, a 6-story RC apartment building was designed using Tekla Structural Designer 2021 software, following Eurocode 8 [14] and the Malaysia National Annex [13]. The beams, columns, and shear walls were constructed with steel reinforcement in consideration. Each model was designed with values of PGA, α_{gR} = 0.08 g, 0.12 g, and 0.16 g, representing Soil Type D in Sabah, Malaysia. The evaluated PGA values and soil type were classified as Medium (DCM). This research considered the grade of concrete, C30/37. This study did not consider the foundation because every site required a different foundation design depending on the soil condition. Table 5 summarizes the PGA, α_{gR} and soil type for each model.

Table 5. The reference peak ground acceleration, α_{gR} and soil type for each model

Model	Soil Type	PGA (g)
Non-seismic	-	-
D-0.08	D	0.08
D-0.12	D	0.12
D-0.16	D	0.16

2.3. Process of Taking Off

During this final phase, the take-off process determined all RC apartment models' required steel reinforcement and material costs. Comparisons were made between the non-seismic and the seismic models, which relied on the parameter of PGA values as steel reinforcement weight per 1 m^3 of concrete. Standard building material prices from the Jabatan Kerja Raya (JKR) were used to determine the material costs for both models [16].

3. Results and Discussion

3.1. Base Shear Force, F_B

Base shear resulted from an equivalent static lateral force applied to the structure's base in any direction due to the earthquake [17]. The estimation of base shear force, F_B, depends on the condition of the site's soil, proximity to probable sources of earthquake activity, the potential of maximum earthquake ground motion, the ductility level and over-strength related to the structure's configurations and total weight, and the structure's actual vibration period due to dynamic loading [17, 18].

The fundamental period of vibration, $S_d(T_1)$ for x- and y- directions had the same values due to the exact dimensions of the structure in x- and y- directions that also influence the base shear force, F_B for x- and y- directions. Based on Table 6, the fundamental period of vibration, $S_d(T_1)$ of the structure was measured at its lowest possible value when α_{gR} was equal to 0.08 g, with values of 1.018 for the x- and y- directions. In comparison, the highest value was found when α_{gR} was set to equal 0.16 g, with values of 2.037 in both the x- and y- directions. Increasing the value of α_{gR} directly increases the value of F_B. Since the value of α_{gR} directly influences the value of F_B, the D-0.08 model had the lowest value of F_B, equal to 7,371.4 kN in both the x- and y- directions. Meanwhile, the D-0.16 model had the highest value of F_B, equal to 14,742.8 kN in the x- and y- directions. According to [4, 8, 17, 18, 19, 21, 23, 24, 25], the value of the parameter α_{gR} affected the $S_d(T_1)$, which in turn impacted the F_B.

Table 6. The values of $S_d(T_1)$ and F_B for each model

Model	Eff. Mass, *m* (ton)	$T_{1(x)}$	$T_{1(y)}$	$S_d(T_{1(x)})$	$S_d(T_{1(y)})$	$F_{B(X)}$ (kN)	$F_{B(y)}$ (kN)
NS	-	-	-	-	-	-	-
0.08M	8513.71	0.624	0.632	1.018	1.018	7371.4	7371.4
0.12M	8513.71	0.624	0.632	1.528	1.528	11057.1	11057.1
0.16M	8513.71	0.624	0.632	2.037	2.037	14742.8	14742.8

3.2. Summation of Concrete Volume

The C30/37 concrete grade was utilized throughout this study. These C30/37 concrete grades were used in the material setup and carried out in the study option before the modelling procedure. Regardless of the research's design considerations, all models' sizes of beams, columns, slabs, and shear walls were identical. Based on Table 7, the concrete volumes for beams, columns, slabs, and shear walls for each model of a 6-story RC apartment building were similar: 2,546.85 m^3. As a result, the concrete cost for each model would be approximately the same.

Table 7. The summation values volume of concrete (m^3) for each model

Model	NS	D-0.08	D-0.12	D-0.16
Beams	484.10	484.10	484.10	484.10
Columns	161.66	161.66	161.66	161.66
Shear walls	471.95	471.95	471.95	471.95
Slabs	1429.13	1429.13	1429.13	1429.13
Total	2546.85	2546.85	2546.85	2546.85

3.3. The Summation Values of The Steel Reinforcement (kg) for The Structures
Table 8 shows the structure's steel reinforcement (kg) summation values. Following Eurocode 8 [14], the seismic designs had to adhere to the "Strong Columns - Weak Beams" principle [20]. Based on Table 8, the summation value of the steel reinforcement (kg) for the structure for the model D-0.16 was the highest for the beams, columns, and shear walls, which were 69,858.49 kg, 39,113.79 kg and 81,357.19 kg, respectively. According to the Table 8, the values of the steel reinforcement for slabs were identical in all model which was 50,670.20 kg. According to the past researcher, increasing values of α_{gR} affected the summation values of the steel reinforcement (kg) for the building [4, 8, 11, 19, 21, 23, 24, 25].

Table 8. The summation values of the steel reinforcement (kg) for the whole structures

Steel Reinforcement (kg)	Building Model No.			
	NS	Soil Type D		
	NS	0.08	0.12	0.16
Beams	54085.94	59502.70	62932.95	69858.49
Columns	34797.95	35260.10	35260.10	39113.79
Walls	47196.44	55540.29	72283.27	81357.19
Slabs	50670.20	50670.20	50670.20	50670.20
Total	186750.53	200973.29	221146.51	240999.67

3.4. The Weight of Steel Required per 1 m³ Concrete (kg/m³)
As shown in Figures 2–6, the weight of steel reinforcement per 1 m^3 of concrete for beams, columns, walls, and the total structures included for the building, model D–0.16 was the highest, which were 144.30 kg/m^3, 241.95 kg/m^3, 172.38 kg/m^3, 35.46 172.38 kg/m^3 and 94.63 kg/m^3, respectively. Based on Figure 2, the steel reinforcement per 1 m^3 of concrete for beams of α_{gR} = 0.08 g, 0.12 g, and 0.16 g increased by 10.01%, 16.36%, and 29.16% compared to non-seismic model, respectively. According to the Figure 3, the steel reinforcement per 1 m^3 of concrete for columns of α_{gR} = 0.08 g, 0.12 g, and 0.16 g increased by 1.32%, 1.32%, and 12.40% compared to non-seismic model, respectively. Based on Figure 4, the steel reinforcement per 1 m^3 of concrete for walls of α_{gR} = 0.08 g, 0.12 g, and 0.16 g increased by 17.68%, 53.16%, and 72.38% compared to non-seismic model, respectively. Based on Figure 5, the values of the steel reinforcement per 1 m^3 of concrete for slabs were identical in all models. According to the Figure 6, the steel reinforcement per 1 m^3 of concrete for beams, columns, walls and slabs for α_{gR} = 0.08 g, 0.12 g, and 0.16 g increased by 7.61%, 18.41%, and 29.05% compared to non-seismic model, respectively. According to research done in the past [8], when the value of α_{gR} was increased, it necessitated an increase in the quantity of steel reinforcement per 1 m^3 of concrete used throughout the structure.

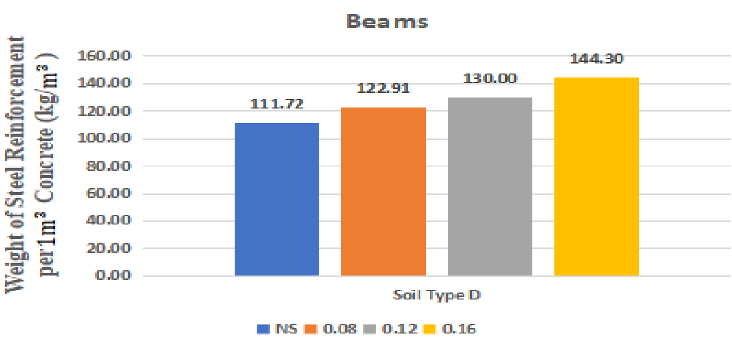


Figure 2. The weight of steel reinforcement per 1 m^3 of concrete (kg/m^3) for beams

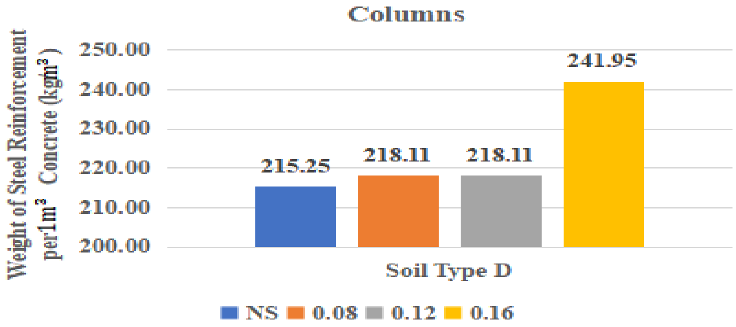


Figure 3. The weight of steel reinforcement per 1 m^3 of concrete (kg/m^3) for columns

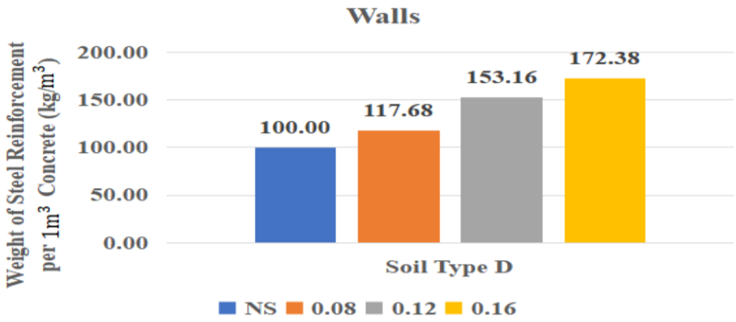


Figure 4. The weight of steel reinforcement per 1 m^3 of concrete (kg/m^3) for walls

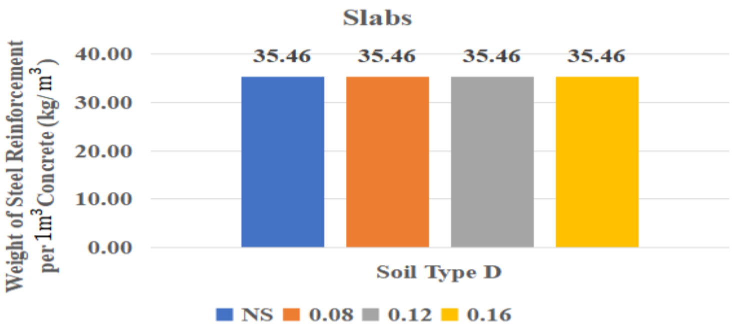


Figure 5. The weight of steel reinforcement per 1 m^3 of concrete (kg/m^3) for slabs

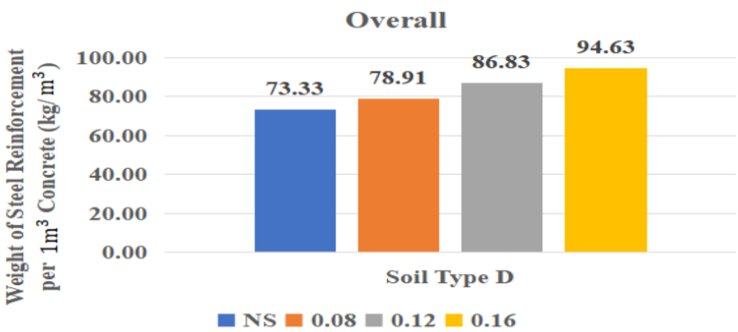


Figure 6. The total structures for the weight of steel reinforcement per 1 m^3 of concrete (kg/m^3)

3.5. Estimation of Total Cost

According to Malaysia's Standard Price for the Year 2021 [16], the price of standardized concrete of grade C30/37 was RM 370.90 per 1 m^3, while the price of steel reinforcement was approximately RM 4.00 per kilogram. The overall cost of the non-seismic model was RM 1,686,924.94. Since the value F_B for the model of non-seismic was the lowest due to the lowest value of the bending moment, M, the model of non-seismic's concrete volume and steel-reinforced expenses were also the lowest. As shown in Figure 7, the overall cost of model D-0.16g was RM 1,900,448.41. Since the value of F_B for model D-0.16 was the highest due to the highest value of the bending moment, M, model D-0.16's concrete and steel-reinforced expenses were the highest. The total cost of structural works went up by 3.3%, 8.0%, and 12.7% for the α_{gR} = 0.08 g, 0.12 g, and 0.16 g, respectively. It is clear, as referred from [4, 8, 12, 19, 21, 22, 23, 24] that the overall cost of the structure would increase as the amount of α_{gR} increased.

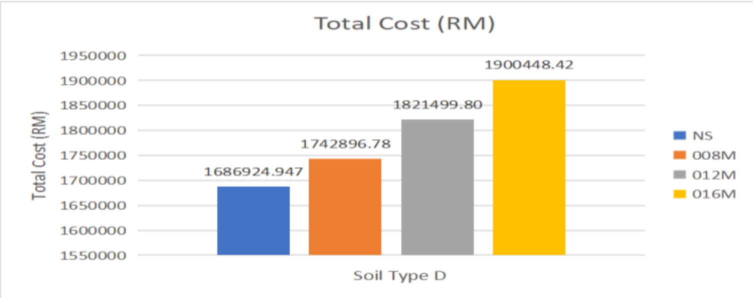


Figure 7. The total cost (RM) for each model

4. Conclusion

Since the value of α_{gR} directly impacts the total quantity of base shear force, F_B, the D-0.16g model exhibited the highest base shear force, F_B, equal to 14,742.8 kN in both the x- and y- directions. The concrete cost for each model would be approximately the same because the concrete volumes for beams, columns, slabs, and shear walls for each model of a 6-story RC apartment building were similar: 2,546.85 m^3. The summation value of the steel reinforcement (kg) for the structure for the model D-0.16 was the highest for the beams, columns, and shear walls, which were 69858.49 kg, 39113.79 kg and 81357.19 kg, respectively, leading to the highest values of the weight of steel reinforcement per 1 m^3 for beams, columns, walls and the total structures included in the building, which were 144.30 kg/m^3, 241.95 kg/m^3, 172.38 kg/m^3 and 94.63 kg/m^3, respectively. The steel reinforcement per 1 m^3 of concrete for beams, columns, walls and slabs for α_{gR} = 0.08 g, 0.12 g, and 0.16 g increased by 7.61%, 18.41%, and 29.05% compared to non-seismic model, respectively. Model D-0.16g needed the most steel per 1 m^3 of concrete to ensure the building could withstand earthquakes. According to the findings, the amount of α_{gR} significantly impacts the steel required for the entire beams, columns, and shear walls. Compared to other models, the steel-reinforced needed in a structure was significantly higher when subjected to a α_{gR} of 0.16 g. Since the total volume of concrete and steel required for the whole structures in model D-0.16g is noticeably higher than that needed in other models, the overall cost of the D-0.16 model was extremely high, which was RM 1,900,448.41. From the findings, it can be concluded that the total cost of the steel reinforcement went up by 3.3%, 8.0%, and 12.7% for the α_{gR} = 0.08 g, 0.12 g, and 0.16 g, respectively.

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