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A study of building performance inspection based on a combination of site-specific response analysis and structural analysis (A case study of the Lighthouse View Tower in Bengkulu City, Indonesia)

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Original scientific paper

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Abstract

This paper presents the implementation of site-specific analysis in observing the performance of a monumental building in Bengkulu City, Indonesia that is called the Lighthouse View Tower. This building was inaugurated in 2012. So far, it is still necessary to present the issue related to the performance of the building after 10 years. The objective of this study is to observe the performance of the building after the strong earthquake occurred. This study is first conducted by performing a site investigation. The information related to the soil profile; ground motion of the strong earthquake that occurred in Bengkulu City is collected. Furthermore, the site-specific response analysis is conducted on the site where the building stands. The results from site-specific response analysis, i.e. the actual spectral acceleration is obtained. The spectral acceleration is then used as the input parameter for finite element analysis to observe the performance of the building. The main goal of this study is to observe the structure health condition. The results show that during the strong earthquake, the structure of the view tower is still reliable and in good condition. Concern regarding the building maintenance should be emphasized. In general, the method implemented in this study could be used as the method to assess the performance of structures in other areas.

Keywords:

site-specific analysis; monumental building; earthquake; spectral acceleration; finite element analysis

1. Introduction

Bengkulu City of Indonesia, the capital city of the Bengkulu Province, is located in the west coastline of Sumatra Island. This city is also known as one of the vulnerable cities in Indonesia to undergo earthquakes (**Farid and Mase, 2020**). Within the last two decades, at least two strong earthquakes with magnitudes more than M_w 7.0 occurred on the west coastline of Sumatera Island and yielded massive impact to structural buildings in Bengkulu City (**Mase, 2018**). Therefore, the importance of an earthquake study in Bengkulu is prioritized to support the seismic hazard mitigation in Bengkulu City (**Mase et al., 2021a**).

As a developing city in Indonesia, Bengkulu City, has started to enhance its establishments (**Mase, 2020**). One of areas in Bengkulu City that has significantly grown is China Town, located on the coastline of Bengkulu City. In this area, several monumental buildings were established by colonizer, before independence and the local government even existed. One of the monumental buildings established by local government is the Lighthouse View Tower. This building was inaugurated in 2012. This building functioned as the view tower to monitor ocean waves, especially once a strong earthquake happened in Bengkulu City. However, this monumental building is now becoming one of the destinations where people in Bengkulu City spend their holiday time. Ten years after its establishment, monitoring of the tower has still not been performed. On the other side, this building's visitors are increasing year by year. This indicates that the tower has frequently attracted visitors. Therefore, it is important to check the structure's performance, especially under dynamic loads, such as earthquakes.

A building performance is influenced by several conditions, such as earthquakes, materials, and sites. A building is designed based on the authorized seismic design code, which should give the best safety for the people staying there. Therefore, it is important to inspect the building performance during an earthquake. To inspect the performance of a structural building, the site-specific response analysis combined with finite element modelling can be implemented. The use of finite element analysis on civil engineering problems, such as structural engineering, pavement and geotechnical engineering has been presented by several researchers. Several studies conducted by **Likitlersuang et al. (2013)**, **Mase (2017)**,

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Zhang and Ren (**2019**), **Xu et al.** (**2019**), **Chheng and Likitlersuang** (**2018**), **Hsiung et al.** (**2021**), **Jamsawang et al.** (**2021**), and **Mase et al.** (**2022**) have explained that the use of a finite element is appropriate to predict stability problems, such as deep excavation, pavement, liquefaction analysis, soft alluvium deposits, and slope failure. In addition, several researchers, such as **Patricier et al.** (**2008**), **Chandak et al.** (**2012**), and **Li et al.** (**2021**) have mentioned that the implementation of finite element modelling for structural engineering could result in the appropriate results. Therefore, the use of a finite element model to solve issues in civil engineering could provide results that are consistent with field conditions (**Li et al., 2021; Mase et al., 2022**).

Veinović et al. (**2007**), **Mase** (**2017b**), **Mase et al.** (**2019**), **Sukkarak et al.** (**2021**), and **Mase et al.** (**2021**) mentioned that soil and building damage must be an issue during the earthquake. This is because seismic propagation wave could result in the resonance effect to the soil and structure that could contribute to more significant damage. Therefore, it is also important to consider the site's effects in the earthquake resistance design for a building. **Mase et al.** (**2018**) mentioned that non-linear site-specific analysis could be implemented to obtain actual spectral acceleration for a structural building. The spectral response obtained from site-specific analysis may be used for consideration in the design of a building. Several studies conducted by **Tanapalungkorn et al.** (**2020**); **Likitlersuang et al.** (**2020**); **Mase et al.** (**2021a**) had mentioned that to ensure the actual earthquake effect, the seismic hazard assessment should be applied in a structural design. At the stage of structural design, the structural analysis should be performed by considering the seismic hazard assessment. **Patricier et al.** (**2008**) revealed that the evaluation of a structural building can be implemented under the framework of finite element modelling. The structural analysis could provide the information where the vulnerability zone in the building is concentrated (**Li et al., 2021**). **Chandak** (**2012**) suggested that analysis of the response spectrum can be used to inspect the performance of a structural building.

The integrated method to inspect the performance of a structural building is important. In the integrated method, the simulation of an earthquake could reflect the dynamic load that would be received by the building and the response of the site during an earthquake could be applied to inspect the building. Therefore, the integrated method combining site response analysis and structural analysis could be reasonably implemented to measure the actual performance of a building during an earthquake. **Yuliastuti et al.** (**2021**) mentioned that the use of response analysis before and after construction can be implemented to inspect a strategic site that is important to support the lifeline of a facility. In line with the importance of the integrated method of site-specific response analysis and structural analysis, this paper presents the combination analysis between site-specific response analysis and structural analysis based on the response spectrum. The site investigation is conducted at the site. An inspection of the existing concrete quality is performed. One-dimensional site-specific response analysis is conducted to obtain the response spectrum at the ground surface. Furthermore, a finite element simulation for structural analysis considering the response spectrum is conducted to observe the distribution of weak zones of structures. In general, this study could reflect the performance of a structural building considering an earthquake. The results of this study may become a recommendation for local government in developing the study area for a local heritage in Bengkulu City, Indonesia.

2. Material and Method

2.1. Study Area

Misliniyati et al. (**2018**) mentioned Bengkulu City that is located on the west coast of Sumatra Island, is known as one of the most vulnerable areas to earthquakes in Indonesia (see **Figure 1**). Bengkulu is surrounded by several active tectonic sources, such as the Sumatra Subduction, Mentawai Fault, and Sumatra Fault (**Mase et al., 2021b**). According to **Natawidjaya et al.** (**2006**), the activity of the Sumatra Subduction had resulted in several mega-earthquakes in the western coastal area of Sumatra, such as the M_w 8.9 earthquake in 1797 and the M_w 9.1 in 1833. **Mase** (**2020**) also mentioned that the activity of the Sumatra Subduction had resulted in two strong earthquakes in Bengkulu City within the last 20 years, i.e. the M_w 7.9 Bengkulu-Enggano Earthquake in 2000 and the M_w 8.6 Bengkulu-Mentawai Earthquake in 2007. Those strong earthquakes had resulted in huge damage in Bengkulu City. For two active faults, **Natawidjaya and Triyoso** (**2007**) and **McCloskey et al.** (**2010**) revealed that both the Mentawai and Sumatra faults had also triggered strong earthquakes, such as the M_w 6.8 Liwa Earthquake in 1994 and the M_w 7.6 Padang Earthquake in 2009.

As elaborated in the previous paragraph, the position of Bengkulu as an earthquake prone area has revealed that the earthquake impact should be considered for structural design. The Lighthouse View Tower is located in the coastal area of Bengkulu City, which **Mase** (**2017, 2018**) based their study on since this area was suspected as one of the vulnerable areas to undergo earthquake impact during the M_w 8.6 Bengkulu-Mentawai Earthquake in 2007. **Figure 1** shows the layout of the study area corresponding to the existing situation. The tower's height is about 50 m in total, with a circle base. Each side of the base of the tower has a width of 4 m at the base. The tower has 3 main parts, namely the semi-basement section, vertical circulation, and the viewing platform. The viewing platform functions as a post-earthquake monitoring of sea wave heights or as a tsunami warning observation site (**Department of Public Works of Bengkulu**

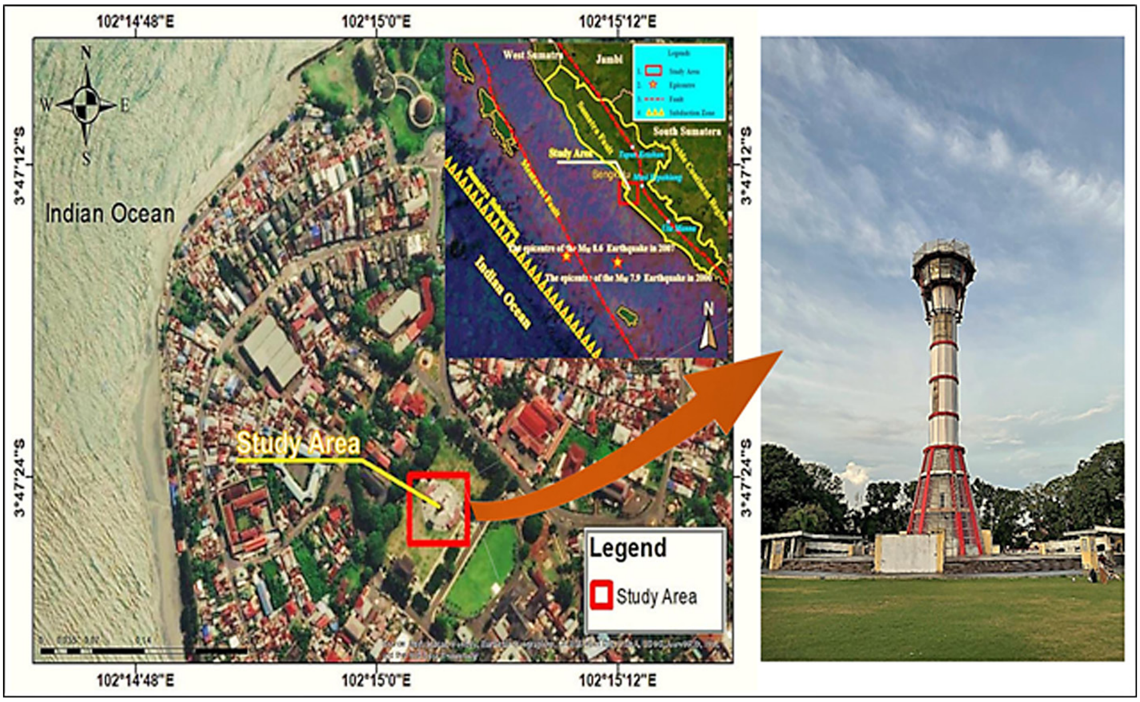


Figure 1: Study Area (basic map modified from **Mase (2020)** and **Google Earth (2022)**)

Province, 2018). In line with this, site investigation data is conducted in the study area and the results of the site investigation are presented in **Figure 2**. There are two field measurements conducted in this study. The first one is boring test as well as standard penetration test (SPT) to determine the soil profile and to measure soil penetration, and the second one is multichannel analysis of surface wave (MASW) to measure shear wave velocity (V_s). In this study, there are three site investigation data presented, i.e. the soil profile, uncorrected and corrected (SPT and $(N_1)_{60}$) values and the V_s profile. SPT is conducted up to 18 m. At this depth, the maximum value of the SPT value has been reached. Therefore, MASW is not only addressed to predict shear wave velocity but also to estimate the layer below maximum depth obtained from SPT. In **Figure 2**, there are 8 soil layers underlain by a rock surface. First layer is dominated by fine grained soils (SP) with thin thickness. This layer (about 0.6 m thick) could be the man-made layer during the construction of the tower. The clay layer is found from 0.6 to 3.4 m depth, which is composed of organic soils to clay and silty clay (CH-OH and CM). The sand layer is generally found from 3.4 to 18.4 m. Based on site investigation, the sandy soils in the study area consisted of silty sand, dense sand, very dense sand, and gravelly sand (SM, SW, and GS). Sandstone and a soft rock surface are found below 18.4 m. In terms of soil penetration, the soil penetration at the site generally increases with depth. It is reflected by the distribution of SPT-N value and V_s. The larger V_s and SPT-N, the deeper depth and vice versa. Based on the MASW results, the site investigation data also showed that the engineering bedrock surface in the study area is found at depth of 23.4 m, with V_s of 796 m/s. According to **Mase et al.** (**2022**), the position of the engineering bedrock is important for site-specific analysis. This surface can be assumed as the place where the seismic wave starts to propagate (**Qodri et al., 2021**).

2.2. The Lighthouse View Tower

Figure 3 presents the structure of the Lighthouse View Tower in Bengkulu City. The height of the tower is about 50 m in total. The first section, called the semi-basement section, is located about 3.5 m below the surface. This section was first used as the office for building management and as a small museum which exhibited the story of the Bengkulu Government. The second section is the body section of the tower, which is called the vertical circulation. In this section, access to go to the top of the tower is provided. This section is about 36 m high. The main section of the building is the viewing platform. This section is 10.5 m in height. This section is addressed as the monitoring location for tidal waves in the Indian Ocean. This tower is addressed to observe the fluctuation of sea water levels and as a tsunami early warning system component.

The tower is constructed by a combination of reinforced concrete and steel. The construction of reinforced concrete is used for the semi-basement and vertical the circulation, and the construction of steel is used for the viewing platform. The inspection to the quality of material has been performed to check the existing material quality after 10 years. In this study, the hammer test to check the concrete quality is conducted for several important sections. In general, there are several main structure components inspected as summarized in **Table 1**

Table 1 Summary of structural components

Types of Structure	Dimension (cm)	Code	Characteristics of concrete compression (f_c') (MPa)	Characteristics of Bar/Steel's yield strength (f_y) (MPa)
Beam	30 × 60	B 30 × 60	15	-
Column	40 × 40	C 40 × 40	59	-
Column	60 × 60	C 60 × 60	28	-
Column	40 × 60	C 40 × 60	21	-
Sloop	20 × 40	S 20 × 40	21	-
Platform	15	P.15	21	-
Platform	12	P.12	21	
Steel	250 × 125	IWF 250 × 125	15	240
Steel	150 × 100	IWF 150 × 100	41	240
Shear Wall	15	SW 1	21	-
Shear Wall	12	SW 2	21	-

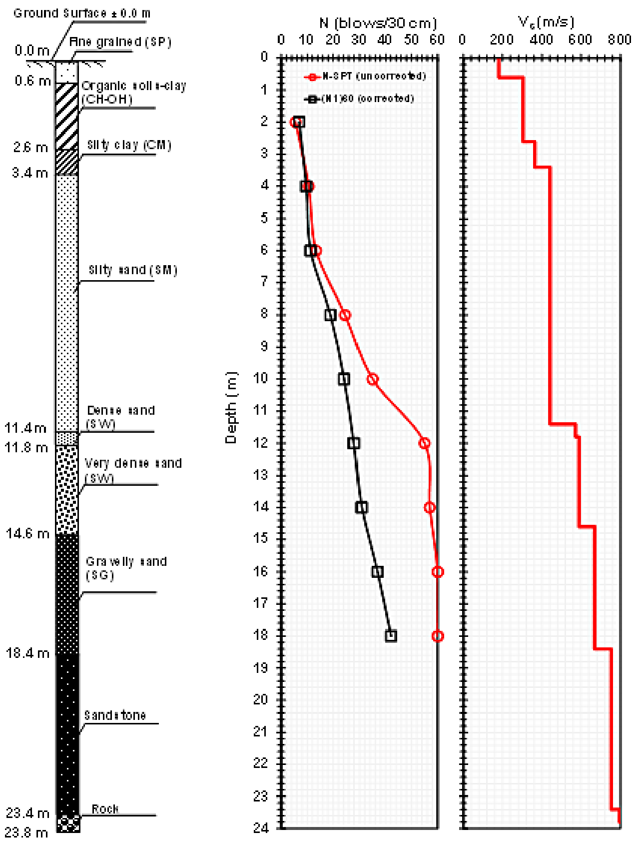


Figure 2: Site investigation data

and the typical structure dimensions used in this study are representatively presented in **Figure 4**. In **Table 1**, it can be observed that there are several column types constructed to support the building. In addition, sloop, beam and platform are also used in the tower. The range of compressive strength is observed to vary from 15 to 59 MPa. The structure also uses a shear wall with compressive shear strength of about 21 MPa. In general, it can be estimated that the tower tends to have a stronger column than beam. It is very important for a vertical building to withstand the effects of earthquakes, thus a vertical structure should be more retained than a horizontal structure. For steel construction, several types of steel beams are used in the tower. The steel beam is generally used as the viewing platform section. For the tower, the platform is steel profile of I Wide Flange (IWF) 150 ´ 100, whereas IWF 250 ´ 125 is used as the supporting beam. For analysis, the yield strengths of materials (f_y) for concrete's bar and steel are 390 MPa (deformed bar), and 240 MPa (plain bar and steel).

2.3. Research Framework

To achieve the goal of this study, the integrated work between site-specific response analysis and structural analysis is performed. The illustration of analytical concept implemented in this study is presented in **Figure 5**. In **Figure 5**, there are three main frameworks implemented in this study. The first one is seismic hazard assessment. Seismic hazard assessment is addressed to obtain the most significant earthquake in Bengkulu City. A study conducted by **Mase** (**2017, 2018**) explained that within the last two decades, the M_w 8.6 Bengkulu-Mentawai Earthquake had resulted in the maximum damage intensity level in Bengkulu City. Therefore, the earthquake could be considered as the most significant earthquake in Bengkulu City. **Mase** (**2017a**) also implemented the spectral matching method to estimate the target spectra and ground motion for engineering bedrock (see **Figure 6**) on the west coast of Bengkulu City. In that study, **Mase** (**2017**) considered the recorded ground motion of the M_w 8.6 Bengkulu-Mentawai Earthquake recorded at the Sikuai Island Seismic Station, which is located 168 km north of the earthquake's epicentre) (**Centre for Engineering Strong Motion Data** (**CESMD**), **2017**) as the matched ground motion. Hence, it is able to be used for seismic ground response analysis in this study. Based on **Mase** (**2017**), peak ground acceleration in the study area during the earthquake is about 0.154g. The ground motion presented in **Figure 6** is then used as the input motion for seismic ground response analysis.

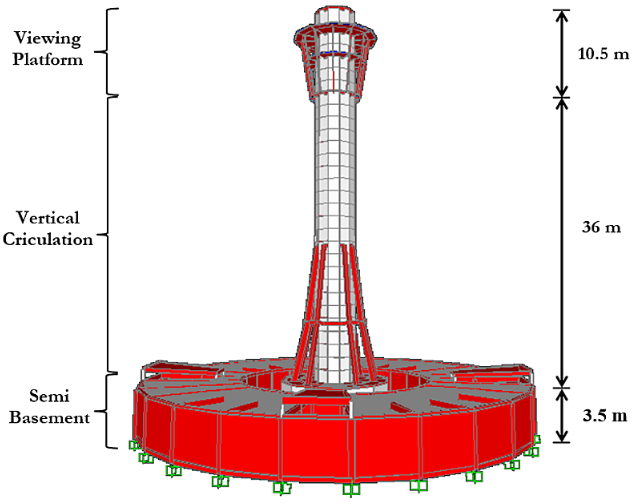


Figure 3: Front view of the Lighthouse View Tower

The second main framework implemented in this study is site-specific response analysis. This stage may be conducted after the seismic hazard assessment to define the most significant earthquake is conducted. The framework of site-specific response analysis had been introduced by various researchers. **Nugroho et al.** (**2020**) mentioned that site exploration related to geological engineering is important to determine site characteristics. The information related to sediment thickness and the position of bedrock is important in site-response details (**Mase et al., 2022**). **Qodri et al.** (**2021**) mentioned that the concept of seismic ground response analysis is initiated by propagating a seismic wave at the engineering bedrock. According to **Adampira et al.** (**2015**), knowledge regarding the position of the engineering bedrock is very important in performing the analysis. **Miller et al.** (**1999**) indicates that the engineering bedrock surface can be assigned for the layer having V_s of 760 m/s. For soil parameters, the assumption of soil dynamic properties is considered based on various studies conducted by many researchers, such as **Seed and Idriss** (**1970**) for sandy soils, **Vucetic and Dobry** (**1991**) for clayey soils, and **Menq** (**2003**) for coarse materials. The summary of parameters for site-specific response analysis is presented in **Table 2**. In **Table 2**, several soil properties are used in the analysis. They are soil thickness, unit weight (g), and V_s. Those properties are obtained based on the site investigation data presented in **Figure 2**. According to elastic theory, the maximum shear modulus (G_{max}) can be estimated from V_s (**L'Heureux and Long, 2017**). There are several curve fitting parameters that are suggested by **Hashash et al.** (**2020**). The parameters are b, s, b, and d. The details on this parameter can be found in **Hashash et al.** (**2020**).

Once a seismic wave propagates through the layer, soil responses, such as acceleration at each layer, spectral acceleration at each layer can be obtained. In this study, one-dimensional site-specific response analysis is implemented to obtain the ground motion at the surface.

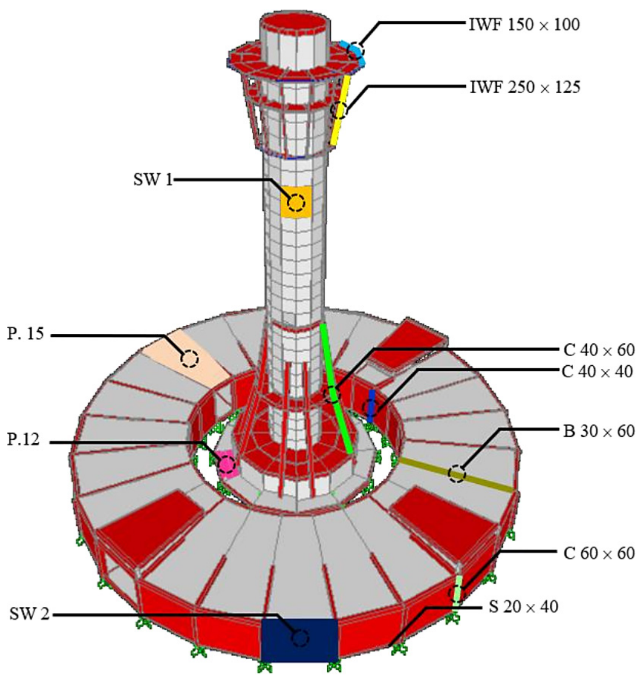


Figure 4: The typical structural dimension of the Lighthouse View Tower

The pressure dependent hyperbolic model from **Hashash et al.** (**2020**) is used as a soil model in the analysis. The model was originally proposed by **Park and Hashash** (**2001**). The model was developed based on the hyperbolic model, which was introduced by **Matasovic** (**1993**). A pressure dependent hyperbolic model emphasizes on the hysteresis loop during cyclic loading. The model defines the backbone curve of a hysteresis loop based on the hyperbolic function, which was first recommended by **Dunchan and Chang** (**1970**). In the simulation of seismic wave propagation, the model performs non-linear analysis by defining the increment of time in the structure of a lump-mass system. The outcomes resulting from site-specific response analysis that is used as the input for structure analysis is spectral acceleration at the base of the structure.

The third main framework performed in this study is structure analysis to observe the performance of the structure during an earthquake. A procedure to perform the dynamic analysis for structure evaluation is the spectral response method. According to **Chandak** (**2012**), spectral acceleration has been affected by various geophysical and seismological parameters, such as earthquake magnitude, site classification, and so on. Therefore, to obtain the appropriate spectral acceleration, the procedure of seismic ground response analysis should first consider the mentioned factors (**Bommer and Avicedo, 2004**). In line with the framework of structure analysis, a finite element method for structural dynamic analysis may become the alternative (**Patricier et al., 2008**).

In this study, the response of the structural building, including the internal forces as bending moment diagram (BMD), shear force diagram (SFD), and normal

Table 2 Summary of dynamic properties and parameters for site-specific response analysis

Layer Name	Thickness (m)	Unit Weight (γ) (kN/m³)	V_s (m/s)	Damping Ratio (%)	Ref. Strain (%)	Ref. Stress (MPa)	Max. Shear Modulus (G_{max}) (kN/m²)	Curve fitting parameters (Hashash et al., 2020)			
								b	s	b	d
SP	0.6	18	182	0.370	0.066	0.180	58,179	1.545	0.855	0	0
CH-OH	2	17	304	0.894	0.050	0.180	153,921	1.620	0.915	0	0
CM	0.8	17	363	1.307	0.030	0.180	220,036	1.605	0.915	0	0
SM	8	18	442	0.370	0.066	0.180	345,039	1.545	0.855	0	0
SW	0.4	19	573	0.193	0.094	0.180	610,398	1.560	0.945	0	0
SW	2.8	20	590	0.193	0.094	0.180	682,611	1.560	0.945	0	0
SG	3.8	21	669	0.889	0.018	0.180	921,178	1.470	0.870	0	0
Sandstone	5	22	752	0.874	0.021	0.180	1,220,143	1.560	0.870	0	0
Rock	0.4	24	796	0.355	0.022	0.180	1,488,898	1.605	0.870	0	0

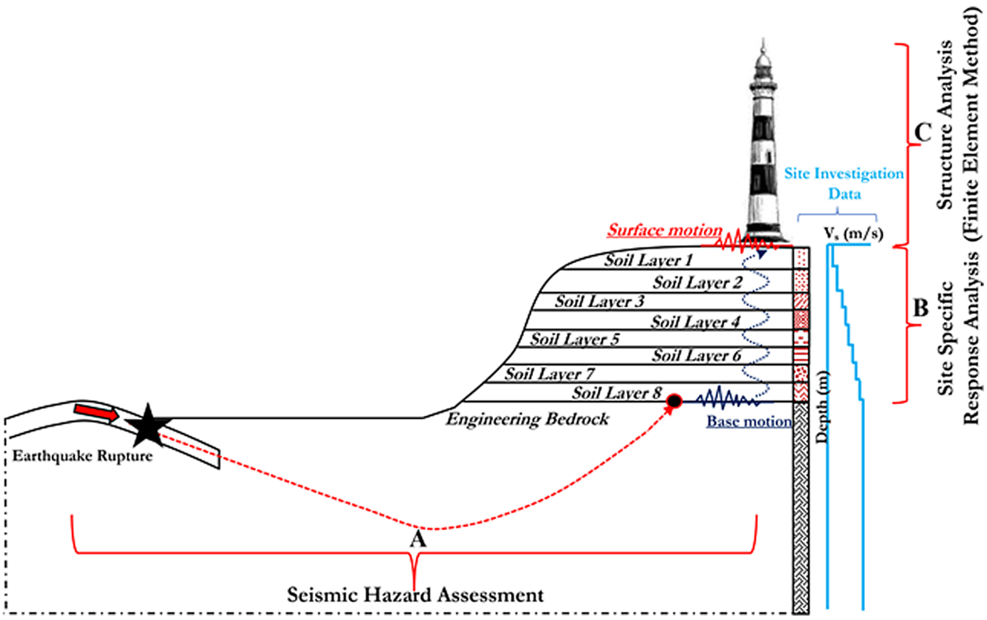


Figure 5: Main concept of the study

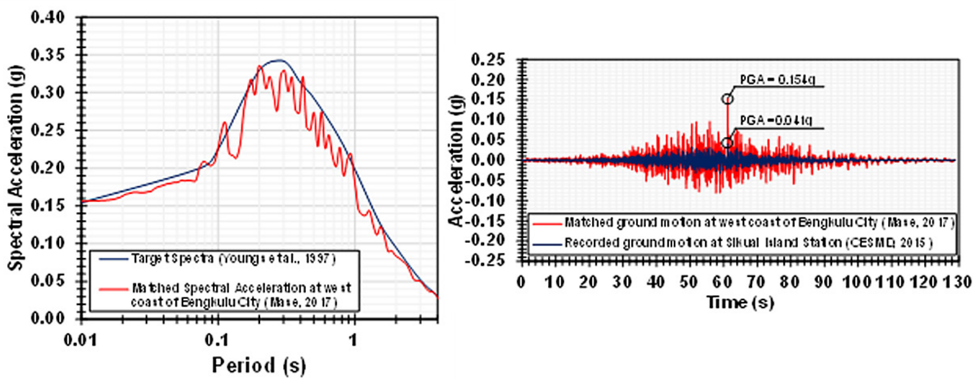


Figure 6: Spectral analysis and ground motion used for site (modified from **Mase (2017)**)

force diagram (NFD) is presented. The performance of the Lighthouse View Tower is evaluated based on the interpretation of the distribution of internal forces. In general, the results of this study could explain the actual condition of the tower's building performance. The results are also able to deliver knowledge related to the integrated work in evaluating the seismic performance of buildings, especially for the monumental buildings.

3. Results and Discussion

3.1. Result of site-specific seismic response analysis

As elaborated in Section 2, the seismic hazard assessment to produce the input motion at the engineering bedrock for the study area is considered based on the previous study conducted by **Mase** (**2017**). In this study, the ground motion suggested by **Mase** (**2017**) for the west coast of Bengkulu City is used. In this section, the results of site-specific seismic response analysis are presented. **Figure 7** shows the profile of maximum acceleration resulted from site-specific response analysis. **In Figure 7**, it can be observed that during seismic wave propagation, the propagated wave at the engineering bedrock tends to be larger at the ground surface. This indicates that the ground motion is amplified. It should be noted that amplification is the comparison between peak ground acceleration at the ground surface and peak ground acceleration of input motion. Based on **Figure 7**, peak ground acceleration at the ground surface is about 0.211g and peak ground acceleration of input motion is 0.154g. Therefore, the amplification factor during seismic wave propagation at the site is about 1.4. **Mase** (**2018**) revealed that based on the ground motion prediction during the Bengkulu-Mentawai Earthquake, peak ground acceleration in Bengkulu City, especially in the coastal area of Bengkulu City, is observed to vary from 0.211 to 0.212g. It showed that the peak ground acceleration based on ground response analysis is generally consistent with the prediction presented in the previous study. In addition, according to **Mase** (**2020**), the amplification factor in the coastal area of Bengkulu City during the Bengkulu Mentawai Earthquake was about 1.4 to 1.5. Therefore, it can be concluded that the result of this study is in line with the previous study.

Figure 8 presents time-history of ground motion and the spectral acceleration comparison at the site. From **Figure 8**, several spectral accelerations including input motion spectral acceleration, spectral acceleration at Layer 1, and spectral acceleration at Layer 4 are compared to each other. It is noted that spectral acceleration at Layer 1 is presented to show the spectral acceleration at the ground surface, whereas spectral acceleration at Layer 4 is presented and used as the input motion for structural analysis. It can be observed that both spectral accelerations at Layer 1 and Layer 4 are larger than the spectral acceleration of input motion. This indicates that there is spectral amplification during the seismic wave propagation. Spectral acceleration from site-specific response analysis is also compared to the seismic design

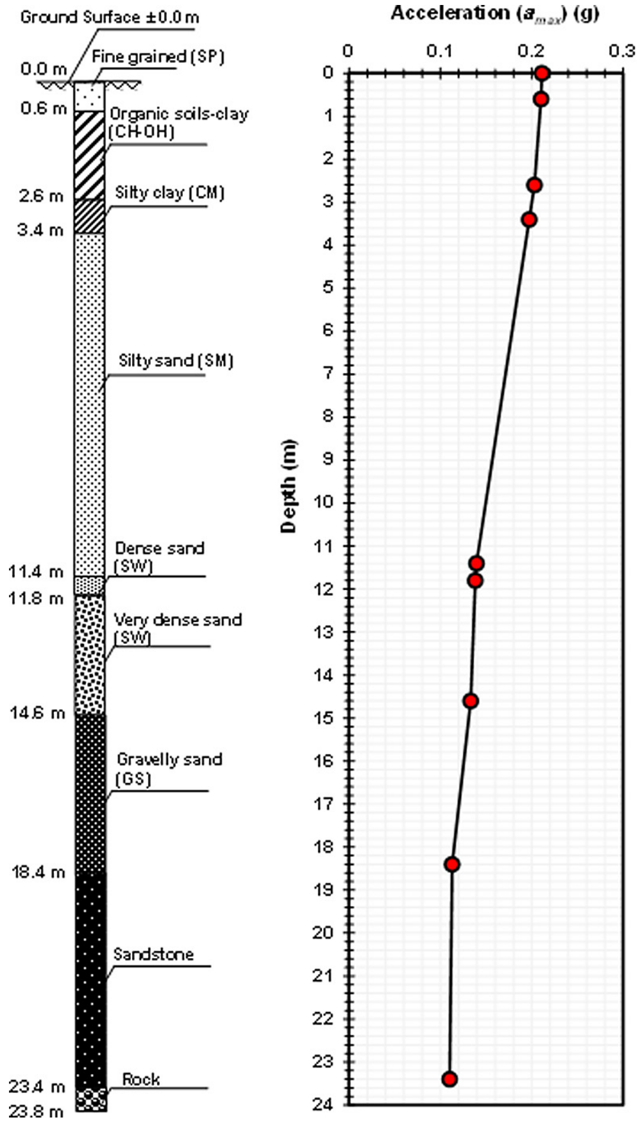


Figure 7: Maximum acceleration profile

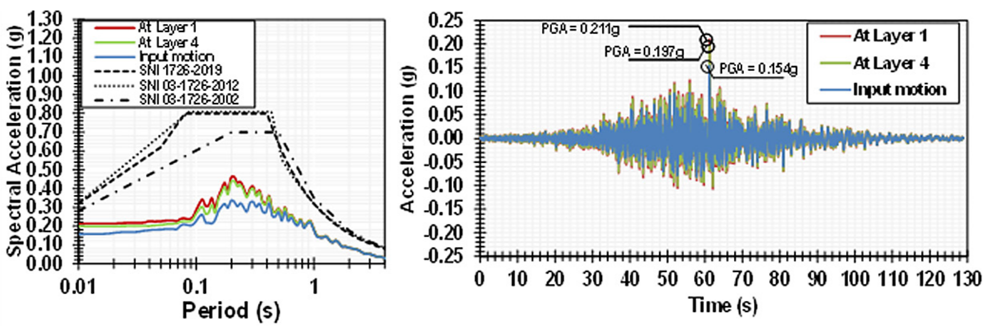
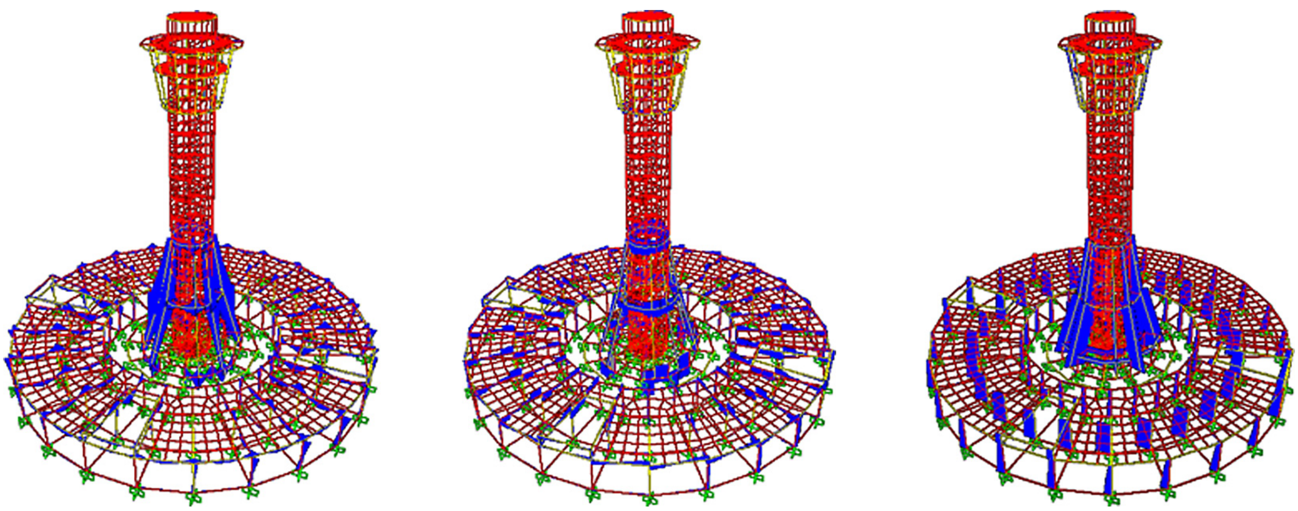


Figure 8: Comparisons of spectral acceleration and time history of acceleration

codes for Bengkulu City. The Tower had been planned before 2012; hence, the structure was planned based on the past seismic design code i.e. **SNI 03-1726-2002** (**2002**) that was still valid at that time. In 2012, the Government of Indonesia released the updated seismic design code called **SNI 03-1726-2012** (**2012**). This means that at the time of the building was opened for the public, the updated version of seismic design code had been valid. Now, the most updated seismic design code of Indonesia is **SNI 03-1726-2019** (**2019**). Therefore, a building constructed in this present time should follow the updated seismic design code. It is shown that design spectral accelerations for Bengkulu City are generally larger. This indicates that if the tower was designed considered the seismic design code, the tower would be relatively resistant to earthquake impact. However, it is important to observe the actual performance of the tower based on the structural analysis. **Figure 8** also presents a comparison of time history of acceleration. It can be seen that in layer 4, the peak ground acceleration (PGA) at the site is about 0.197. There is no significant difference between peak ground accelerations at Layer 1 (ground surface) and Layer 4. In Layer 4, the basement is constructed. Therefore, for structure analysis, the spectral acceleration at Layer 4 is used. The result of structure analysis is presented in the next section.

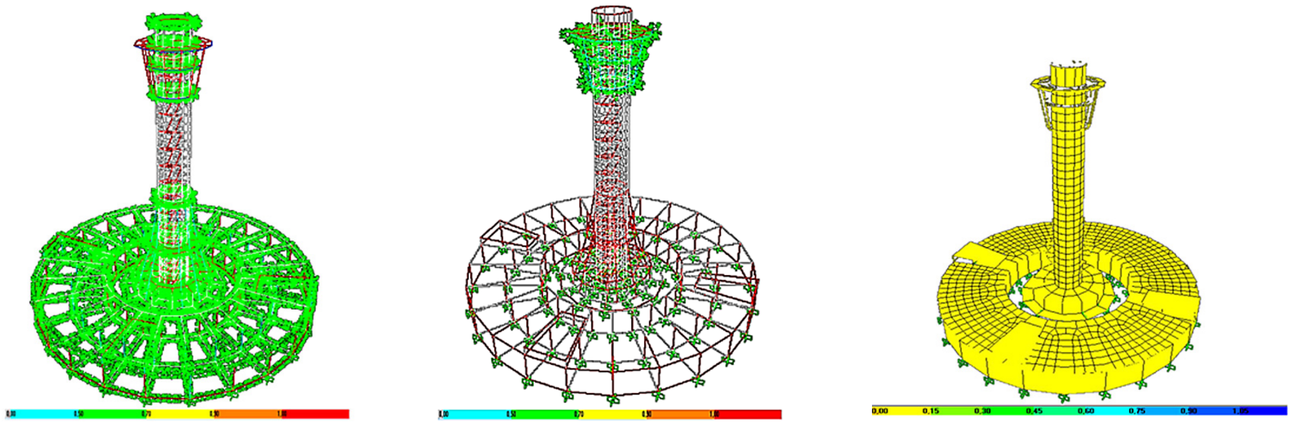
3.2. Structure's Response

In this study, the structure analysis is considering load combinations including death, live, and earthquake loads. **Figure 9** presents the distribution of internal forces resulted from structure analysis. In **Figure 9**, the internal forces are obtained based on the combination loads, including death load, live load, and earthquake load that are applied simultaneously. **Figures 9a, 9b**, and **9c** present the distribution of internal forces for bending moment diagram (BMD), shear force diagram (SFD), and normal force diagram (NFD). **Table 3** presents the maximum internal forces performing on each structure applied in the



(a) (b) (c)

Figure 9: Internal forces diagrams (a) BMD, (b) SFD, and (c) NFD



(a) (b) (c)

Figure 10: Structural condition checking based on stress ratio (a) concrete structure, (b) steel structure, (c) shear wall and platform

Table 3 Summary of maximum internal forces

Type of Structure	Dimension (cm)	Code	Maximum Internal Forces		
			Moment (kNm)	Shear Force (kN)	Normal Force (kN)
Beam	30 x 60	B 30 x 60	88.09	64.25	11.04
Column	40 x 40	C 40 x 40	34.60	10.32	0.02
Column	40 x 60	C 40 x 60	69.64	19.79	1.84
Column	60 x 60	C 60 x 60	51.61	15.28	0.21
Sloop	20 x 40	S 20 x 40	141.52	153.08	13.31
Steel	250 x 125	IWF 250 x 125	5.80	2.66	0.00
Steel	150 x 100	IWF 150 x 100	0.13	0.88	0.00
Platform	15	P.15	16.08	18.82	7.61
Platform	12	P.12	15.26	81.04	182.28
Shear Wall	15	SW 1	16.08	18.82	7.61
Shear Wall	12	SW 2	15.26	81.04	182.28

Lighthouse View Tower. In general, the maximum bending moment resulted based on the analysis is observed to vary from 0.13 to 141.52 kNm. For shear and normal forces, they are observed to vary from 0.88 to 153.08 kN and 0 to 182.28 kN, respectively.

Figure 10 presents the structure checking based on an evaluation conducted using finite element simulation. **Figure 10a** presents the concrete checking after the structure analysis. It is shown by the parameter called stress ratio. Stress ratio is the comparison between internal forces and ultimate allowable strength of the profile. A good condition can be reached once the stress ratio is less than 1 (green shading). In this study, it is shown that for the concrete structure, the stress ratio is observed to vary from 0.5 to 0.75. In **Figure 10a**, the concrete response based on structure analysis shows that the performance of the concrete structure is relatively good. Based on the evaluation and analysis result, it can be concluded that the concrete condition is still in good shape to respond to seismic impact during an earthquake.

For the performance of steel material, the evaluation result is shown in **Figure 10b**. It can be observed that the steel structure on the Lighthouse View Tower of Bengkulu City shows good performance. Based on **Figure 10b**, the stress ratio is observed to vary from 0.5 to 0.7 (green shading). Similar to the results presented in **Figure 10b**, the result in **Figure 10b** concluded that the steel installed in the tower structure is still performing well. In line with the design implemented for the tower, the structure is designed by following the seismic design code prevailing at that time. Based on the spectra comparison presented in the previous section, the spectral acceleration from site-specific response analysis is still lower than the seismic design code. The use of higher spectral acceleration could guarantee a better quality of structure performance and it is shown by the evaluation results from finite element simulation

Figure 10c presents the structural checking based on stress ratio for shear wall and platform. As presented in **Figures 10a** and **10b**, a similar tendency for shear wall and platform is also shown. Based on the analysis, it can be observed that stress ratio is observed to vary from 0.0 to 0.15 (yellow shading). This indicates that the structure of the shear wall and platform is relatively in good performance to withstand the earthquake load. Overall, based on the evaluation of the structure performance, it can be concluded that the tower's structure is still in good condition to give service for the building's users.

3.3. Concern on the building for future development

The existence of the Lighthouse View Tower is very important to support tourism, historical memory, and to serve its function as a tsunami early monitoring system. It has been verified by the integrated analysis that the building's structure has still been showing good performance as long as it functions. Therefore, it can be roughly concluded that the structure of the tower is still reliable. Nevertheless, concern on the maintenance effort should be also addressed.

One important thing that should be aware is that the position of the tower which is located in the coastal area. It is known that weather in coastal area tends to have a high-salt content (**Su et al., 2020**). It has also been known that the salt-content could influence the durability of engineering materials, such as concrete and steel. In line with this, the structure of the tower is dominated by concrete and steel. Therefore, the effort on the maintenance of these materials should be addressed. The temperature in Bengkulu City is also relatively hot, especially along the coastal area of Bengkulu City (**Mulyasari et al., 2021**). In addition, the climate change impact could result in the extreme change of weather that could also influence the structural building, especially the corrosion effect on steel material (**Almussalam, 2001**) and over cracking due to overheating of the concrete material (**Dong et al., 2021**). Generally, the intensity of storming weather could occur intensively every year in Bengkulu City. In line with this condition, the mitigation efforts to maintain the durability of the materials are important. Another concern also lies on the effort of steel connection reinforcement. As elaborated in the previous section, steel materials are installed at the viewing platform. It is about 40 m above ground surface and this will endanger visitors who are under the tower if the reinforcement's condition on the tower connection is not controlled properly. Therefore, a routine inspection of the materials' condition should be intensively performed.

Finally, since this building may become one of the monumental buildings in the future, it should be given a priority for the maintenance of the building. The existence of the Lighthouse View Tower is also as a landmark of Bengkulu City. The combination between modern building and colonial heritage building is mixed in the location of the Lighthouse View Tower of Bengkulu City. More attention on this building would attract visitors locally, nationally and internationally. This can certainly improve the economy in the China Town area of Bengkulu City in particular, and the Bengkulu Province in general.

4. Conclusion

This paper presents a study of building performance inspection based on a combination of site-specific response analysis and structural analysis (A case study of the Lighthouse View Tower in Bengkulu City, Indonesia). The integrated method of site specific-structural analyses is conducted. The site investigation is conducted to find subsoil information under the building, the ground response and structural analyses are conducted to assess the performance of the building overall. Several concluding remarks can be drawn as follows:

1. Site investigation data revealed that the site is dominated by sandy soils. It is also revealed that the engineering bedrock location in the study area is found at a depth of 23.4 m below ground surface. During the seismic ground response analysis, a seismic wave propagated from engineering bedrock up to ground surface. The analysis shows that the amplification factor is about 1.4. The spectral acceleration obtained from ground response analysis shows that spectral accelerations from the seismic design code are generally higher than the actual ground response. Therefore, it can be concluded that the building constructed under the seismic design code has fulfilled the criteria of design considering the effect of actual ground motion during a strong earthquake in the study area. Overall, the results also showed consistence between the ground motion prediction and the ground motion resulted from this study.

2. A structural analysis using the finite element method showed that the stress ratio for concrete material and steel material presents the evidence that the condition of structure is generally in good performance. This is due to the fact that the design has considered the seismic design code at the time and based on the fact that the spectral acceleration of ground response is actually lower than the spectral acceleration designs. Therefore, the structure design under the condition tends to be also safe if a strong earthquake happen. The experimental test on actual concrete's compressive strength has also showed that the concrete material is also relatively in good performance. In general, the structure has applied a stronger column than beam to maintain the service of the building for the vertical load. Therefore, it can be concluded that the design of the building has considered the long-term effect as the monumental building in the study area.

3. Building maintenance should become the main concern. This is due to the fact that the building is categorised as a monumental building and a landmark of Bengkulu City. The maintenance effort of the building should consider the environmental effect. Regular maintenance of the building could keep the building conditions within good standards. A safe building would deliver comfortable conditions for visitors. This effort would attract local, national, and international visitors and it would improve the economy for people staying near the location.

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SAŽETAK

Analiza pregleda stanja građevine kombinacijom analize seizmičkoga odziva na smjestištu i strukturne analize (studija slučaja svjetionika s vidikovcem u gradu Bengkulu, Indonezija)

Ovaj rad predstavlja primjenu analize stanja na smjestištu monumentalne građevine, svjetionika s vidikovcem u gradu Bengkulu u Indoneziji. Građevina je svečano otvorena 2012. Nakon 10 godina još je uvijek aktualno pitanje strukturnoga stanja građevine, a cilj je ove studije utvrditi njezino stanje nakon snažnoga potresa. Studija je započela provođenjem terenskih istraživanja. Prikupljeni su podatci vezani uz profil tla te je zabilježen najveći pomak tla uslijed potresa koji se dogodio u gradu Bengkulu. Nadalje, seizmička analiza provedena je na mjestu gdje se građevina nalazi. Iz analize seizmičkoga odziva dobiveno je stvarno spektralno ubrzanje. Ono se koristilo kao ulazni parametar za analizu konačnih elemenata pri promatranju postojanosti građevine. Glavni je cilj ovoga istraživanja promatranje strukturnoga stanja građevine. Rezultati istraživanja upućuju na to da je uslijed jakoga potresa konstrukcija vidikovca i dalje pouzdana i u dobrome stanju. Poseban naglasak stavljen je na održavanje građevine. Općenito, metoda provedena u ovoj studiji mogla bi se koristiti kao metoda za procjenu postojanosti konstrukcija u drugim područjima.

Ključne riječi:
analiza na smjestištu, monumentalna građevina, potres, spektralno ubrzanje, analiza konačnih elemenata

Author's contribution

Lindung Zalbuin Mase (Ph.D, Assistant Professor, expert on Geotechnical and Structural Engineering) provided site-specific response analysis and structural analysis, composed the original draft and editing, held funding acquisition, supervision, and project administration. **Recky Yundriesmein** (Ph.D. candidate, researcher, expert on Architecture) provided structural analysis and composed the original draft. **Muhammad Ali Nursalam** (B.Eng, Civil Engineering) provided structural analysis and composed the original draft. **Surya Manggala Putra** (student, Civil Engineering) provided structural analysis and picture editing. **Aza Shelina** (student, Civil Engineering) provided structural analysis and picture editing. **Sahrul Hari Nugroho** (student, Civil Engineering) provided structural analysis and picture editing.