Evaluation of Hospital Building Resilience to Earthquakes Using Soil Response and Finite Structure Dynamics Structure Analysis

Zaky Majid Ibrahim[1]*, Lindung Zalbuin Mase[1], Fepy Supriani[1], Rena Misliniyati[1], & Khairul Amri[1]
[1]Department of Civil Engineering, University of Bengkulu, Indonesia
*Corresponding Author: G1B021080.zakyibrahim@mhs.unib.ac.id

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Abstract *– The city of Bengkulu is the capital of Bengkulu Province, which is the main center for government, health, and education activities. As the capital city, infrastructure development is important due to its proximity to the subduction zone. This study analyzes how the Tino Galo hospital building responds to seismic performance. The study began with a comprehensive field survey to collect geological information at the study site. Referring to various earthquake events at the study site, it is known that earthquakes triggered by subduction are the dominant type of earthquake that occurs. The seismic response of the soil was then evaluated to identify soil movement characteristics, including important parameters such as peak ground acceleration (PGA), spectral response acceleration, and amplification factor. The next step was to simulate earthquake wave propagation using three-dimensional modeling with the Finite Element Method (FEM) to assess the structural response of the building to earthquake shocks. The analysis results show that after evaluation using time history data from both earthquake waves, the building structure elements are in a safe condition. These findings imply that the current structural design can effectively withstand and distribute earthquake loads, so that no dimensional changes or additional reinforcement are required for the Hospital Building. This study recommends the continued application of a combined soil response and structural dynamics analysis method for buildings in earthquake-prone zones, as well as the need to utilise a broader range of earthquake data to improve the accuracy of seismic performance evaluations and support the development of future risk mitigation strategies.*

Keywords: *Earthquake; ground response; Peak Ground Motion; Hospital; FEM*

INTRODUCTION

Planning earthquake-resistant building structures is crucial in Indonesia, given that most of its territory is located in areas with moderate to high seismic intensity, which has the potential to cause significant damage. Many regions in Indonesia are highly vulnerable to seismic hazards because they are located at the meeting point of four tectonic plates: the Eurasian, Indian, Australian, Pacific, and Philippine plates. The interaction between these plates has transformed many areas, including Sumatra, Java, Sulawesi, Nusa Tenggara, and Papua, into high-risk zones (Sengara et al., 2020).

Bengkulu City, which serves as the capital of Bengkulu Province, acts as a main center for government operations, healthcare services, and educational institutions. As the provincial capital, the development of its infrastructure is of critical importance, particularly given its location near a subduction zone, as shown in Figure 1, The city is situated near the point where the Indo-Australian and Eurasian tectonic plates meet. Because these plates are constantly moving, Bengkulu is considered one of the areas in Indonesia that faces a high risk of earthquakes and is particularly vulnerable to the effects of major seismic activities (Mase et al., 2021).

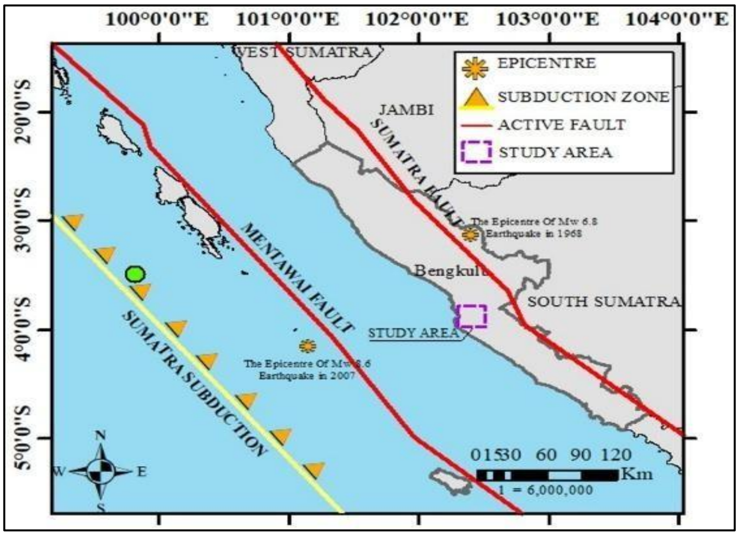


Figure 1. Seismotectonic conditions and epicentre of major earthquakes in Bengkulu Province

On 23 May 2025, an earthquake with a magnitude of Mw 6.3 struck the city of Bengkulu, causing damage to many homes and public facilities, as shown in Figure 2. Not only that, Bengkulu has experienced major earthquakes, one of the largest earthquakes ever to occur in Bengkulu being the 2007 Bengkulu-Mentawai earthquake with a magnitude of Mw 8.6, which caused widespread damage. The 2007 Bengkulu-Mentawai earthquake is still used as a reference in the design of earthquake-resistant structures (Mase, 2017).

Figure 2. Post Mw 6.3 earthquake in bengkulu city in 2025

Ng et al., (2019) argue that population growth has driven an increase in infrastructure needs as a major driver of socio-economic development. This condition is in line with the establishment of Tino Galo Hospital in the city of Bengkulu. In 2023, this hospital underwent expansion with the addition of new buildings, including an emergency unit, treatment rooms, and supporting facilities, to support the optimisation of quality care, research development, and innovation in health services. In this case, seismic hazard mitigation is essential to guarantee the safety and adequacy of the building structure. Thus, the potential for damage due to earthquakes must be considered in building planning to minimise damage. According to research conducted by Mase et al., (2022), FEM-based structural dynamics simulation has become the standard in earthquake resistance analysis. This method can effectively analyze the intricate relationship between the structure and the ground, leading to a more precise understanding of how the building responds dynamically. Building upon the findings of Kostinakis et al., (2018), the dynamic interaction between a structure and its supporting soil is a key factor influencing structural performance during seismic events. In this research, the Finite Element Method (FEM) was utilized to develop a three-dimensional (3D) model, enabling the spectral visualization of surface ground vibrations derived from one-dimensional seismic response analyses. This includes non-linear effects on foundations and soil to assess their impact on structures. Seismic recording data collected at the research site is essential for assessing how well buildings can handle the forces caused by earthquakes (Pranowo et al., 2024). This process simulates how seismic waves move through soil layers in one direction, producing important information like peak ground acceleration, spectral acceleration, amplification factors, and time-history records. This information helps in understanding how the structure behaves dynamically during an earthquake. Given the high potential for earthquakes, it is very important to understand the extent to which the Tino Galo Hospital structure can withstand earthquakes. It is also important to analyse the building by combining soil response and structural dynamics methods to test the Tino Galo Hospital's ability to withstand a potential megathrust earthquake of considerable magnitude.

RESEARCH METHODS

Study Area

This study was conducted at Tino Galo Hospital, located in Muara Bangkahulu subdistrict, Bengkulu City, as shown in Figure 3. This is a strategic area that is the centre of government, trade, public services, health, and education (Mase et al., 2018). The hospital's location on the coast exposes it to a higher risk of tsunamis triggered by undersea earthquakes, which can damage and destroy coastal areas (Farid & Mase, 2020).

Figure 3. Research Location

The building construction was designed in accordance with Indonesian seismic design standard SNI 1726:2012, which discusses building construction characteristics. As shown in Figure 4, this building has several structural components, such as columns, beams, and slabs. It should be noted that this building was constructed using shallow footplate foundations.

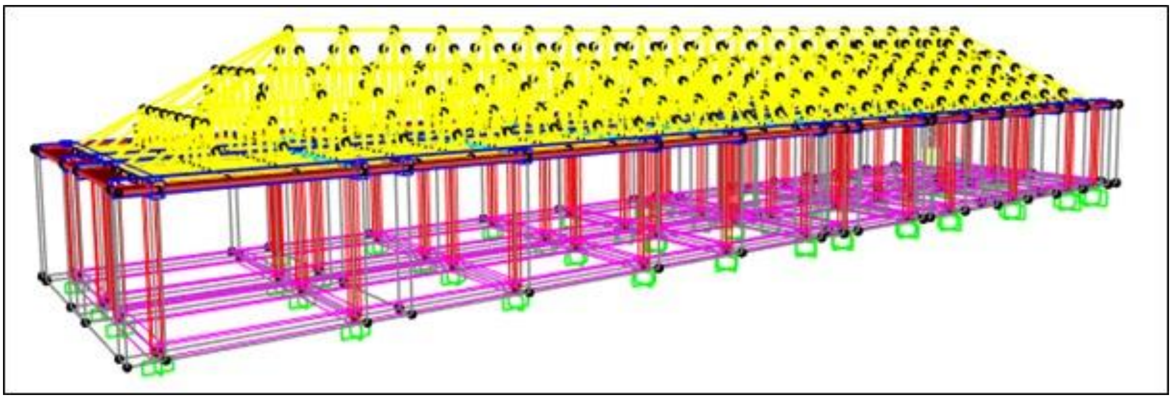


Figure 4. Research Building Modelling

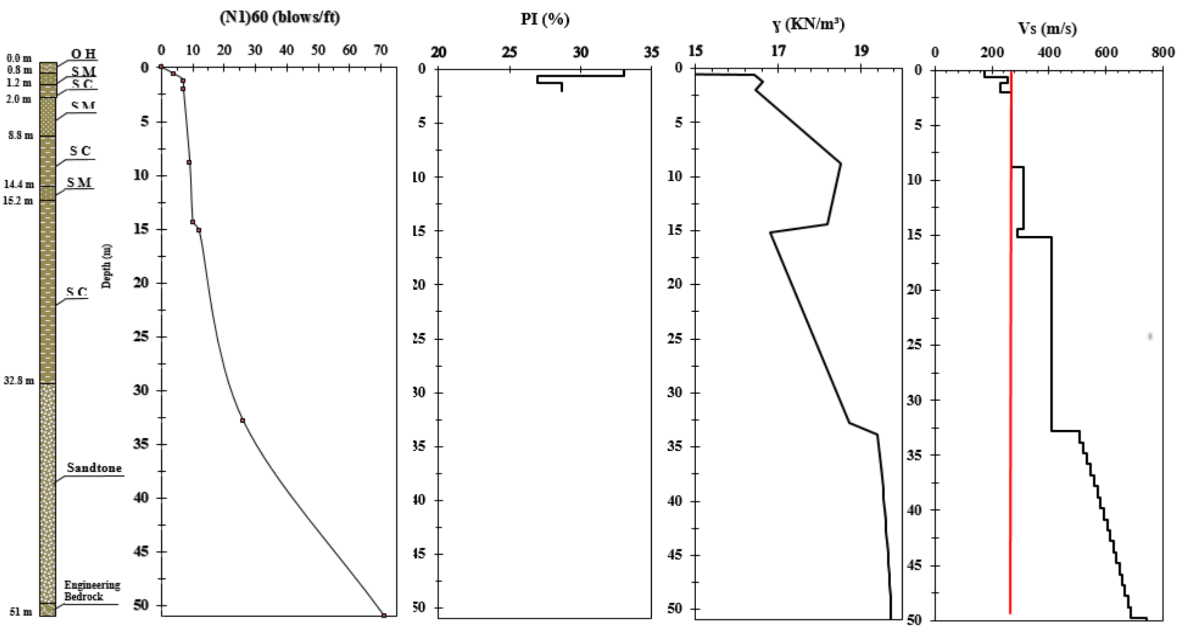


Figure 5. Research Location Investigation Data

The study commenced with detailed field investigations and subsequent calculations of soil parameters, aimed at characterizing the site's geotechnical conditions. As illustrated in Figure 5, the dataset comprises essential geotechnical indicators, including the corrected standard penetration test value (N1)60, shear wave velocity (Vs), unit weight (γ), and plasticity index (PI). These parameters are indispensable for understanding the soil's mechanical response and are critical for assessing seismic vulnerability as well as guiding the design of earthquake-resistant foundations.

The results of geotechnical analysis at the research site show a soil profile consisting of three different layers. The top layer is organic clay (OH), found from the surface to a depth of 0.8 metres. Next, there are layers of sandy silt (SM) and silty sand (SC) that extend from a depth of 0.8 metres to 32.8 metres. The deepest layer, from 32.8 metres to 51 metres, consists of rock, sandstone, and weathered bedrock. Analysis shows that the average shear wave velocity at a depth of 30 metres from the ground surface (Vs_{30}) is 332 m/s with a site class of D. Engineered bedrock is located at a depth of 51 metres, with a depth of 18.2 metres and a Vs of 741 m/s. These geotechnical conditions greatly influence the dynamic response of the soil to seismic activity. Research by Mase et al., (2021), states that in the floodplain area of the Bangkahulu estuary, where this hospital is located, engineered bedrock is generally found at a depth of 5 m to 99 m below ground level.

Combined Soil Response Method and Structural Dynamics Analysis

This study analyses how the Tino Galo hospital building responds to seismic performance. It employs a combined approach of dynamic response analysis and soil characteristic modeling during earthquakes to comprehensively evaluate the interaction between the soil and the structure during an earthquake. If the structure cannot withstand the seismic load and the resulting impact, it can be said to have failed. Analyzing building performance is crucial, especially when dynamic loads caused by seismic activity occur. It is known that earthquake waves often occur in Bengkulu due to the movements caused by the subduction of the Sumatra plate. Historical earthquake data were gathered from several significant seismic events, including the 2007 Bengkulu-Mentawai earthquake, the Mexico earthquake, and the Coyote earthquake. Furthermore, the study involves analyzing the soil response; its function in increasing the intensity of seismic waves as they travel from the bedrock to the surface is especially important (Mase, 2020; Teguh & Erlangga, 2019), as illustrated in Figure 6.

The Finite Element Method (FEM) is integrated to analyze the behavior of structures under dynamic loading conditions. According to Mase et al., (2022), FEM is one of the computational approaches used to analyze soil bearing capacity. Three-dimensional modelling through FEM simulation enables a more accurate evaluation of structural resistance, leading to effective building designs that are safe from seismic risks (Fares et al., 2022).

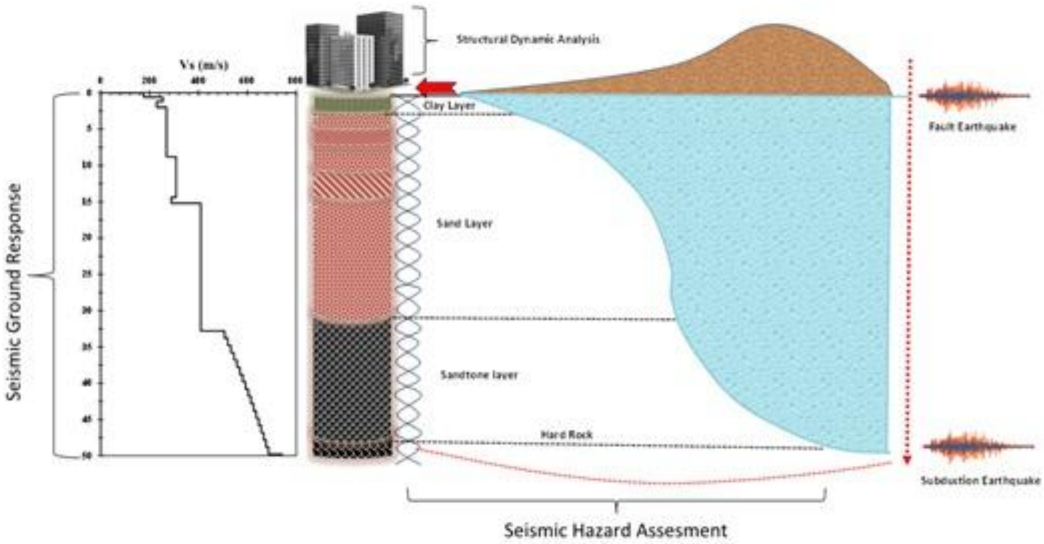


Figure 6. Combined Method Scheme

Ground Motion parameter

Seismic ground response analysis is measured through several key parameters, namely, peak ground acceleration (PGA). One of the parameters obtained from this analysis is the amplification factor, which describes the extent to which ground acceleration increases when seismic waves propagate from the bedrock to the surface. This increase occurs due to differences in soil material characteristics. This occurs because the shear wave velocity (Vs) is generally lower at the surface than at the base of the rock due to softer and less compact soil conditions. This is in line with research (Kumar et al., 2022), which states that with increasing depth, the shear wave velocity increases. To calculate the amplification factor (AF) through one-dimensional seismic response analysis, the maximum acceleration occurring at the soil surface parameter (PGAsurface) is compared with the acceleration occurring in the lower structure (PGAinput) Ghimire et al., (2021). This comparison aims to measure the extent to which the soil characteristics at that location amplify earthquake acceleration. This amplification factor can be calculated using equation 1:

$$AF_{\max} = \frac{PGA_{surface}}{PGA_{input}} \quad (1)$$

Framework Analysis

This study focuses on the evaluation of building inspections and seismic performance, which is a direct response to the implementation of regulations regarding Indonesian seismic design codes. The focus of this study is on the Tino Galo hospital building located in Bengkulu City, which functions as a health service centre. Due to the geographical location of Bengkulu City, which is close to various faults, earthquakes caused by subduction activity are the most frequent type of earthquake. As discussed in the study by Mase, (2020), Seismic ground motion data from the 2007 Bengkulu-Mentawai earthquake, analyzed using a deterministic hazard approach, play a significant role in assessing how the ground responds during seismic events.

The research started with field data collection and soil parameter analysis to assess the soil characteristics of the study area. The next step was to analyse historical data from various earthquake sources. This analysis compared the seismic wave characteristics produced by three categories of earthquakes: strong, moderate, and weak. The data were subsequently modeled, beginning at the bedrock surface and propagating upward to the ground surface, resulting in a ground motion time history that was later analyzed by (Mase et al., 2023). The time history data is then used in structural dynamics analysis, where PGA and spectral acceleration parameters are used as earthquake inputs for building structures. This stage was followed by the determination of structural loading, which involved combining various load types and mass sources. A time-history analysis was performed to evaluate the structure's performance, with a particular focus on the stress ratio. Color changes in the different parts of the structure demonstrated this. Alongside this, the normal force, shear force, and bending moment were calculated to find areas of the structure that might be more vulnerable.

RESULTS AND DISCUSSION

PGA (Peak Ground Acceleration)

Seismic response analysis employing hyperbolic models generates essential parameters, including peak ground acceleration (PGA) and spectral acceleration. The PGA, which measures the highest level of ground acceleration caused by seismic waves traveling from the bedrock to the surface, is an important factor in evaluating how vulnerable a particular location is to earthquakes. Higher PGA values indicate greater potential for earthquake damage and provide information about seismic conditions in the region. PGA can describe earthquake situations and aims to reduce structural damage in the event of an earthquake (Mase, 2020).

Figure 7 shows the PGA profiles that occurred due to the Bengkulu-Mentawai, Mexico, and Coyote earthquakes. The results of the seismic ground response analysis show significant differences between the Peak Ground Acceleration (PGA) values generated by the three different earthquake sources. In the Bengkulu-Mentawai earthquake, the earthquake acceleration increased from 0.119 g to a peak wave of 0.265 g. In the Mexico wave, the earthquake wave acceleration increased from 0.132 g to a peak wave of 0.297 g, while in the Coyote earthquake, the wave acceleration increased from 0.125 g to a peak wave of 0.365 g. The acceleration of the Bengkulu-Mentawai earthquake wave tended to be more stable than that of the Mexico and Coyote earthquakes, which experienced significant changes. The variation in PGA values and amplification factors is strongly associated with differences in shear wave velocity (Vs) across soil layers. Lower Vs values in the surface layer correspond to higher amplification factors. This finding aligns with the study by Misliniyati et al., (2024), which demonstrated that the amplification factor is significantly influenced by wave propagation velocity, where reduced velocities lead to increased amplification, indicating weaker rock strength. The potential damage to hospital buildings caused by these three earthquakes should be taken seriously, but the impact of the Coyote earthquake waves is expected to be more destructive than the Bengkulu-Mentawai and Mexico earthquake waves.

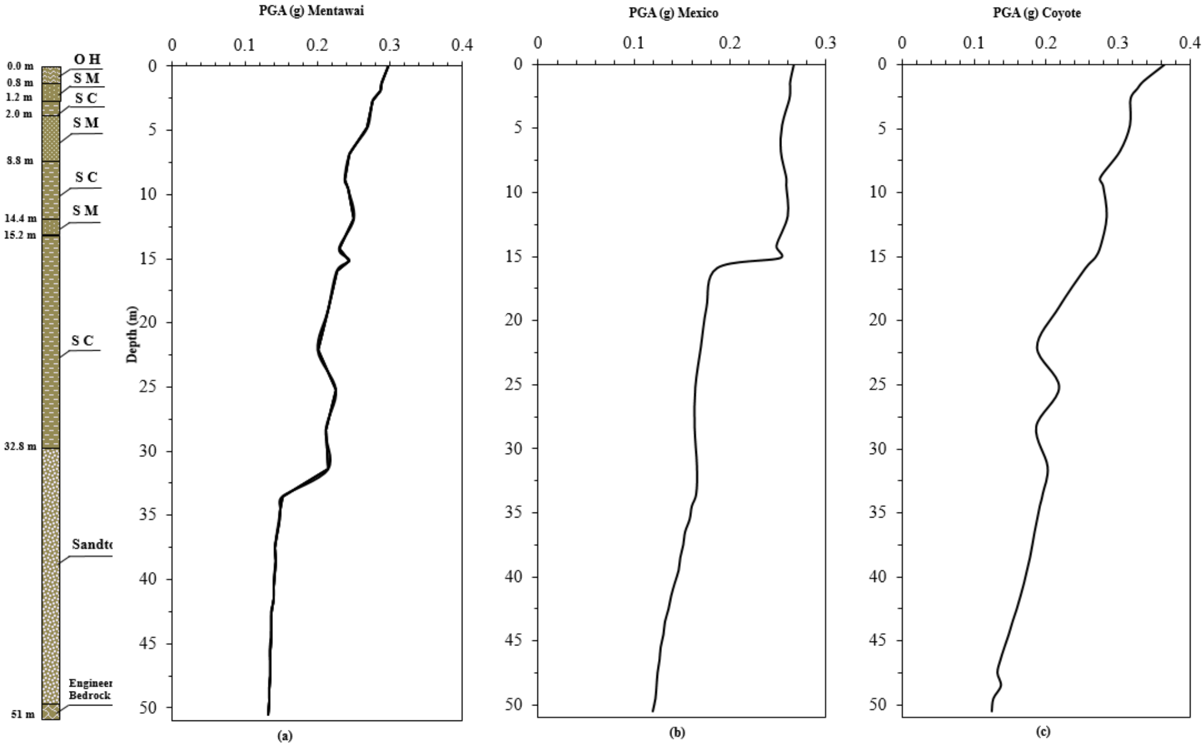
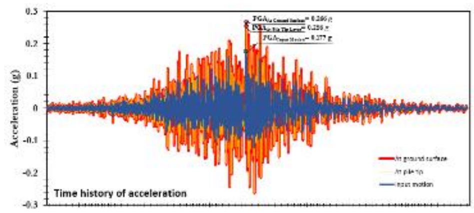


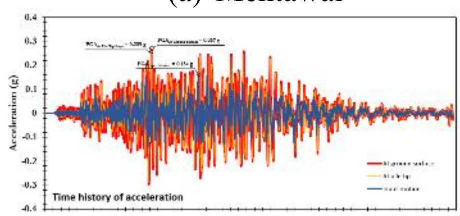
Figure 7. Peak Ground Acceleration Profile of Ground

This study uses a method to analyze how soil responds to seismic activity in a non-linear way. The temporal record of ground acceleration indicates that the peak acceleration associated with the input motion is usually lower than that measured at the ground surface. Ground motion characterization within the time history framework involves multiple parameters, such as the response spectrum and Arias intensity, which are essential for evaluating seismic energy distribution and potential structural impacts (Misliniyati et al., 2025).

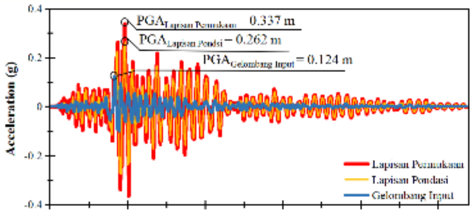
The seismic response analysis in Figure 8 was conducted on three different aspects, namely input movement, surface layer, and foundation tip layer. The ground movement modelled in this study represents the impact of the most influential major earthquakes in this region. This study investigates how earthquake motion propagates and affects the response of various soil and foundation elements. In the study by Qodri et al., (2022), the short period of ground motion indicates the potential for a significant impact on low to medium-rise buildings.



(a) Mentawai



(b) Mexico



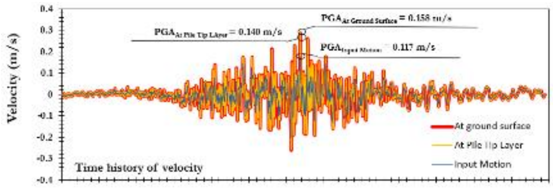
(c) Coyote

Figure 8. Time history of ground motions at ground surface, pile tip layer, and input motion for acceleration (a)Mentawai, (b) Mexico, (c) Coyote

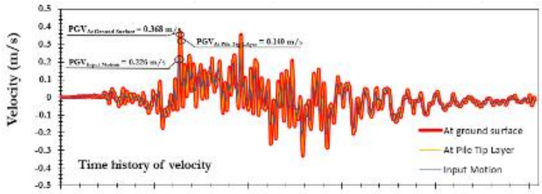
Figure 8 shows the PGA values for the Bengkulu-Mentawai, Mexico, and Coyote earthquake waves. In the Bengkulu-Mentawai earthquake wave, a PGA value of 0.266 g was obtained at the surface layer, in the Mexico earthquake wave, a PGA of 0.267 g was obtained at the soil surface layer, and from the Coyote earthquake, a value of 0.337 g was obtained at the surface layer.

Figure 9 shows the velocity values for the Bengkulu-Mentawai, Mexico, and Coyote earthquake waves. The PGV value on the surface layer for the Bengkulu-Mentawai earthquake wave was 0.158 g, for the Mexico earthquake wave it was 0.368 g, and for the Coyote earthquake wave it was 0.310 g.

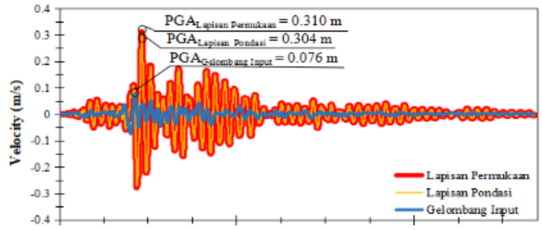
From the acceleration and velocity values, the surface layer tends to be greater than the input movement. The stronger the earthquake and the longer its duration, the greater the structural damage that will occur. Engineers ensure that buildings are designed to withstand strong shocks in accordance with the seismic hazard level. In practice, historical seismic data analysis helps to estimate the duration of ground motion in an area, which is important for designing earthquake-resistant buildings and mitigating disaster risks.



(a) Mentawai



(b) Mexico



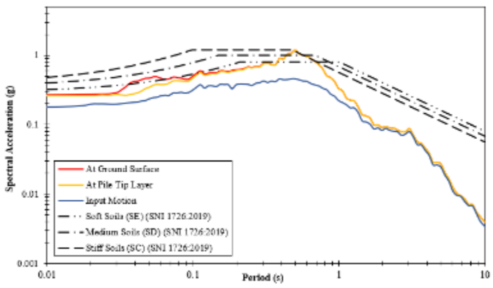
(c) Coyote

Figure 9. Time history of ground motions at ground surface, pile tip layer, and input motion for displacement (a)Mentawai, (b)Mexico, (c)Coyote

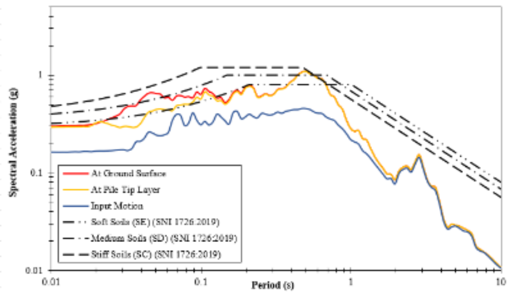
Spectral Acceleration

Structural design must refer to earthquake resistance design regulations for buildings and non-buildings, as stated in SNI 1726:2012, which was later adjusted to SNI 1726:2019 to be relevant to current building developments and functions. In addition, seismic design codes that compare spectral acceleration values from analysis must also be an important consideration in structural design. Figure 9 shows a comparison of spectral acceleration values under three conditions. The results of the analysis indicate that the peak spectral acceleration occurs at the ground surface layer. It was observed that the recorded spectral acceleration at the surface exceeded the values predicted by seismic response modeling, suggesting additional amplification effects. These outcomes are consistent with the research conducted by Qodri et al., (2022), in Banten Province, which demonstrated that the spectral acceleration of the input motion was substantially lower than that at the ground surface, thereby evidencing the phenomenon of motion amplification.

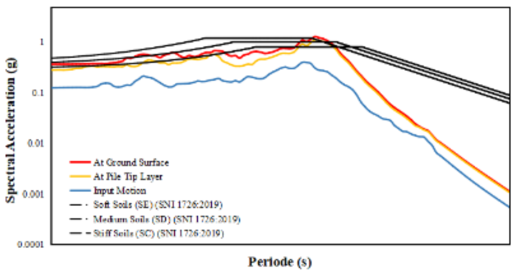
Based on these findings, it can be concluded that Tino Galo Hospital in Bengkulu Province has met the requirements of the current earthquake-resistant structural design code and demonstrates safe performance in the event of an earthquake.



(a) Mentawai



(b) Mexico



(c) Coyote

Figure 10. Spectral acceleration comparison (a)Mentawai, (b)Mexico, (c)Coyote

Dynamic Response of Buildings

The finite element method (FEM) serves as a computational approach for assessing the structural performance of buildings subjected to various loading conditions, including static loads, temporary loads, and seismic-induced pressures. Upon completing the analysis, the structural performance under seismic excitation is assessed by evaluating mass participation across various vibration modes. This parameter reflects the extent to which the building's mass contributes to each mode and is typically represented through mode shapes, which illustrate the characteristic deformation patterns exhibited by the structure when subjected to dynamic forces.

The finite element method (FEM) facilitates the determination of internal force components, namely axial forces, shear forces, and bending moments, that are critical for assessing the structural behavior and safety of building systems. Prior to the application of earthquake loads, the axial force values were observed to range from 2,861 to 21,620 kN, the shear forces varied between 6,034 and 63,301 kN, and the maximum bending moments ranged from 4,103 to 47,919 kNm, as summarized in Table 1. After incorporating seismic loading into the model, these values increased markedly, with axial forces ranging from 1,013 to 102,230 kN, shear forces between 6,355 and 71,035 kN, and maximum bending moments escalating to values between 4,173 and 92,588 kNm, as presented in Table 2.

Tabel 1. Assessment of structural forces before seismic loading

Structure Element	Normal Force (kN)	Shear Force (kN)	Moment (kNm)
Beam 1	21.620	23.621	18.011
Beam 2	5.142	6.162	4.103
Column 1	0.129	63.301	47.919
Sloof	-2.861	6.034	14.548

Table 2. Assessment of structural forces after seismic loading

Structure Element	Maximum Element Strength								
	Mentawai			Mexico			Coyote		
	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)
Beam1	98.512	67.004	69.141	96.204	69.142	69.509	102.23	71.035	73.252
Beam2	23.152	6.448	4.173	24.191	6.355	4.212	24.409	8.822	6.831
Column1	1.013	62.653	47.543	1.245	63.262	47.862	1.547	68.263	55.048
Sloof	32.281	35.921	91.271	35.174	36.372	91.624	36.91	38.432	92.588

Based on the results of a comprehensive evaluation, the Tino Galo Hospital analysis showed good structural performance before and after being subjected to seismic loads. Figure 11 shows the distribution of stress ratios in structures subjected to seismic loads. If the stress ratio in a building exceeds one, then dimensional changes are required, or structural reinforcement is required if the building already exists. In this study, the hospital building was modeled by applying seismic loads obtained through detailed earthquake response analyses, enabling a comprehensive assessment of the structure's performance under seismic excitation. The evaluation of structural responses under three earthquake time history scenarios revealed that all structural elements of the hospital building satisfied the safety criteria. Therefore, neither dimensional adjustments nor additional reinforcement were necessary to ensure the structural integrity of the facility.

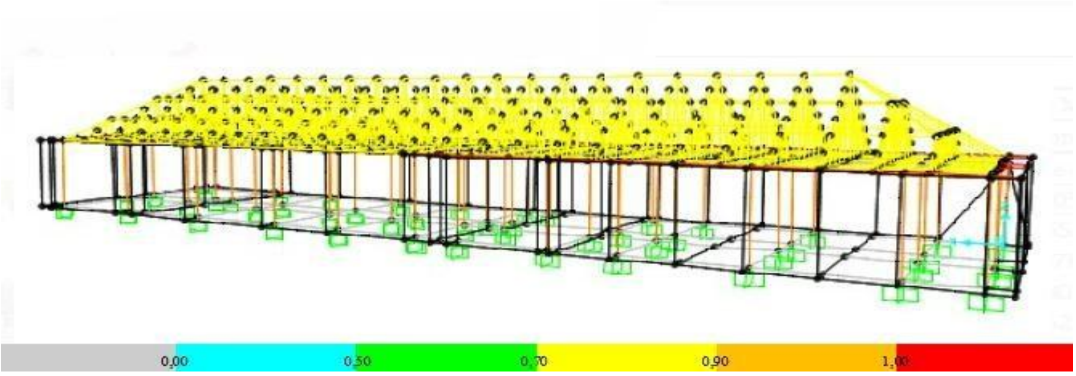


Figure 11. Concerete Structure Stress ratio

CONCLUSION

The structural performance of the Tino Galo Hospital building was assessed in accordance with the Indonesian National Standard (SNI) 1726:2019, which provides the fundamental framework for designing earthquake-resistant buildings. After finalizing the structural modelling and finite element analysis, the evaluation process proceeded to examine the building's seismic performance by analyzing mass participation within its vibration modes. The performance of the Tino Galo Hospital during a strong megathrust earthquake was analysed by combining soil response and structural dynamics analyses. To support comprehensive investigations, seismic acceleration time history data and amplification factors were employed, with a particular focus on analyzing soil–structure interaction. This methodology proved to be highly effective in identifying structural vulnerabilities and assessing seismic performance. Based on the analysis of three earthquake sources in Bengkulu-Mentawai, Mexico, and Coyote, the Coyote earthquake had the most significant impact. This can be seen from the maximum PGA value of 0.365 g and the best amplification on the surface.

Furthermore, after assessing the behaviour of the structure by incorporating two sets of historical earthquake vibration data, the structural response results showed that the structural elements of the building were in a safe condition. This can be seen from the stress ratio, which shows that no components have weakened. Additionally, this study emphasizes the importance of integrating soil response analysis with structural modeling in earthquake performance evaluations. Overall, these findings provide insights to strengthen earthquake resilience strategies in high-risk zones and can serve as a reference for developing earthquake design and risk mitigation in the future.

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