http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 10 No 2 2025

RESEARCH ARTICLE

# Resonance and Damping Ratio Analysis of the Baiturrahman Mosque Tower Based on Earthquake Ground Shaking

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Received: Apr 13, 2025; Accepted: Jun 30, 2025.
DOI: 10.25299/jgeet.2025.10.02.21982

**Abstract**

Aceh is a region of tectonic activity, characterized by high seismicity. This inherent seismic hazard endangers the stability of vertical structures, such as mosque towers. The objective of this study is to analyze the dynamic characteristics of the Main Tower of the Baiturrahman Grand Mosque by estimating its natural frequencies and damping ratios. These parameters are used to evaluate the structural vulnerability of the mosque. The study obtained data from multilevel microtremor measurements on each floor of the tower. These measurements were analyzed using two methods. The Horizontal to Vertical Spectral Ratio (HVSR) method identified the dominant frequency in the basement. The Random Decrement Method (RDM) determined the natural frequency and damping ratios at each level of the structure. The results indicate that the natural frequency of the tower ranges from 1.16 to 4.32 Hz, with a damping ratio of 0.91% to 22.97%, which is within the established range for reinforced concrete structures. The substandard value can cause the building to oscillate easily when earthquake shocks occur. The analysis identified the upper floors, specifically 3 and 4, to be the primary sites of resonance, with ratios reaching 11-12%. The significant negative correlation between height and natural frequency indicates that the upper part of the structure is more prone to low-frequency earthquakes. The implications of this study are significant in light of their potential to enhance the understanding of the structural resonance risks and provide a technical basis for planning mosque towers in earthquake-prone areas.

**Keywords:** Seismicity, Microtremor, Vulnerability, Ground Motion, Earthquake.

## 1. Introduction

Aceh is situtated in the seismically active region followed by high percentage of risk, hazard and vulnerability in Indonesia where it has been represented by the distribution of the several major earthquakes from 1821 to 2024 (Qadariyah et al., 2018; Nurana et al., 2021; Pasari et al., 2021a; Asnawi et al., 2022, Muksin et al., 2023a; Asnawi et al., 2024). There are 16 active faults associated with the Sumatra fault and four subduction zones extending from the west to the north of Aceh province (Pusgen, 2017; Muksin et al., 2023b; Asnawi et al., 2023; Arifullah et al., 2024). The city of Banda Aceh is geographically close to the Aceh and Seulimeum fault segments, which makes it highly susceptible to seismic activity. The vulnerability of Banda Aceh to earthquakes is influenced not only by tectonic factors, but also by local geological conditions. The region is dominated by alluvial soils overlying a basin structure, which contributes to an increase in seismic wave amplification up to 1.5-2 times higher than normal conditions (Irsyam, 2017; Simanjuntak et al., 2018).

An example case was occurred on November 2020, with a magnitude of M6.0, resulting in damage to buildings in the Aceh region and its surroundings as shown in Fig. 1 (Muksin et al., 2023b). In addition, the major earthquake and tsunami event on December 26, 2004, with a magnitude of M9.0, also reinforced the importance of earthquake hazard mitigation in the region (Simanjuntak and Olymphia, 2017; Asnawi et al., 2023). The high level of building damage during earthquakes is also influenced by soil-structure interaction, non-seismic building design, lack of damping systems, and the phenomenon of seismic resonance.

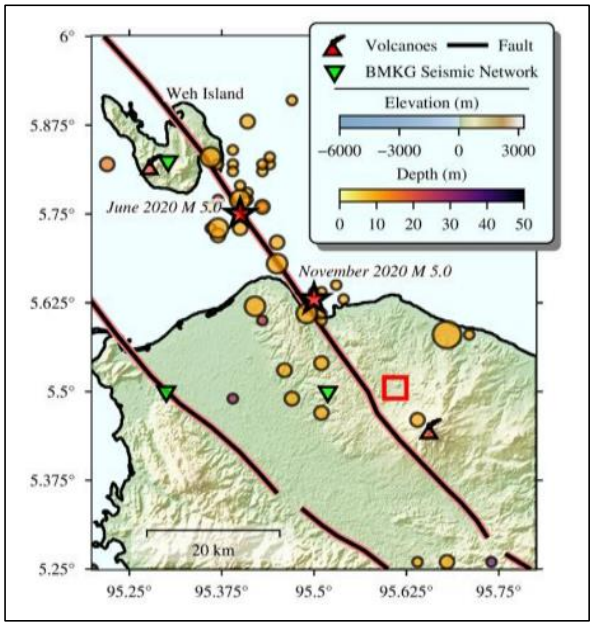


**Fig. 1.** Seismicity map shows the earthquake distribution in the Aceh region (Asnawi et al., 2023). The red square depicts an example location where local peoples felt the shaking with III – IV MMI.

This resonance occurs when the natural frequency of a structure coincides with the dominant frequency of earthquake waves, amplifying vibrations and increasing the risk of structural failure (Geli, 2016; Chopra, 2017; Simanjuntak et al,

2023). Public buildings are among the most vulnerable places during an earthquake, as they are frequented by the public and serve as places for evacuation or emergency response (Pasari et al., 2021b; Lamonge et al., 2024). One of the most common types of public buildings in Banda Aceh are mosques, as the majority of the population is Muslim. Several earthquakes in Indonesia have caused significant damage to mosque structures, including high tower. Examples include the Jami Nur Abdullah Mosque in Pidie Jaya, whose minaret collapsed in the 2016 earthquake, and the structural damage to more than 260 mosques in Mamuju from the M6.2 earthquake in 2021. This indicates that mosque tower are highly vulnerable to seismic damage, which requires further study in the context of mitigation.

Microtremor measurement methods, using approaches such as horizontal-to-vertical spectral ratio (HVSR) and random decrement method (RDM), have been widely used in studies to analyze the dynamic response of buildings (Chopra, 2017). Several previous studies have shown that tall buildings, including towers, tend to have lower natural frequencies than short buildings and are more prone to resonance during earthquakes (Sungkono et al., 2014; Hadianfard et al., 2017; Ashayeri et al., 2021). Therefore, studying the relationship between building height, natural frequency, and damping is very important to assess the structural vulnerability, especially for vertical buildings such as mosque tower.

Based on this background, this study aims to analyze the effect of height on the natural frequency, resonance level and damping ratio of the tower of the Baiturrahman Grand Mosque in Banda Aceh. This study will evaluate the dynamic characteristics of each of the four floors of the tower, with the main objective of identifying the level of structural vulnerability to earthquake hazards. The results of this study are expected to serve as a basis for improving the design of earthquake-resistant mosque buildings, especially in the high part of the minaret, as well as a reference for future seismic disaster risk reduction efforts.

## 2. Methodology

The research was conducted at the Baiturrahman Grand Mosque located in Banda Aceh City, Aceh with coordinates 5.5537o LU and 95.3174o BT. The main tower has a height of 53 meters with 4 floors and an area of 90 $m^2$ (Azman, 2004). The data used in this measurement are the results of microtremor surveys on each floor of the tower consisting of 4 points and 1 point in the basement as shown in Figure 1. Signal recording was carried out with a duration of 60 minutes and recorded using a seismometer sensor. The sensor used is the Geobit S-20 near broadband seismometer sensor which has a 3-component recording with a sampling rate of 100 Hz and is equipped with a 24bit digitizer.

The microtremor data results were then analyzed using the HVSR and RDM methods. The analysis begins with HVSR processing at the basement point. Nakamura (2008) mentioned that the HVSR method is very effective for identifying natural frequencies in sedimentary layers. Besides being easier and more efficient, this technique is also able to estimate the resonance frequency directly without having to know the shear velocity structure and subsurface geological conditions first (Rahmania, 2017). HVSR (Horizontal Vertical Spectral Ratio) is defined in the equation (Nakamura, 1989) given below.

$$HVSR = \frac{\sqrt{A(f)_{EW}^2 + A(f)_{NS}^2}}{A(f)_Z}$$

Data analysis was continued by applying the Random Decrement Method (RDM) to determine the damping ratio value of the natural frequency tire of each floor of the building. RDM is known as a random time series transform method in the energy reduction of free vibration of building structures (Nashir, 2013). The goal is to cancel the random component in order to obtain a poor free vibration curve of the estimated damping and natural frequency. The principle of Random Decrement Method (RDM) analysis is to respond from a random frequency system to be filtered into random excitation and determine the damping ratio of the building with a bandpass filter process in evaluating the natural frequency of the fourier spectrum (Tunggal, 2013).

The natural frequency data of each floor and basement is processed to determine the level of resonance. If the building frequency is close to or is a multiple of the natural frequency of the soil material, then seismic vibrations can cause resonance in the building, which in turn increases the stress in the building structure (Gosar, 2010). To determine the resonance ratio of the building and identify the resonance level, equation 2 is used.

$$R = \left|\frac{fb-ft}{ft}\right| x\ 100\%$$

where R is the building resonance ratio (%), fb is the building frequency (Hz); and ft is the ground natural frequency (Hz). Resonation values are categorized into 3 (Gosar, 2010) where values below <15% include hazard class, 15-25% include high, and >25% include low.

## 3. Results And Discussion

Based on the HVSR curve, the Masjid basement location under the main tower shows the peak of the curve at frequency (fo) 1.33 Hz and amplitude 0.76 (Figure 3). The fo value indicates that the Masjid location has an alluvial sedimentary soil type based on the Kanai soil type classification (Verecha et al., 2022).

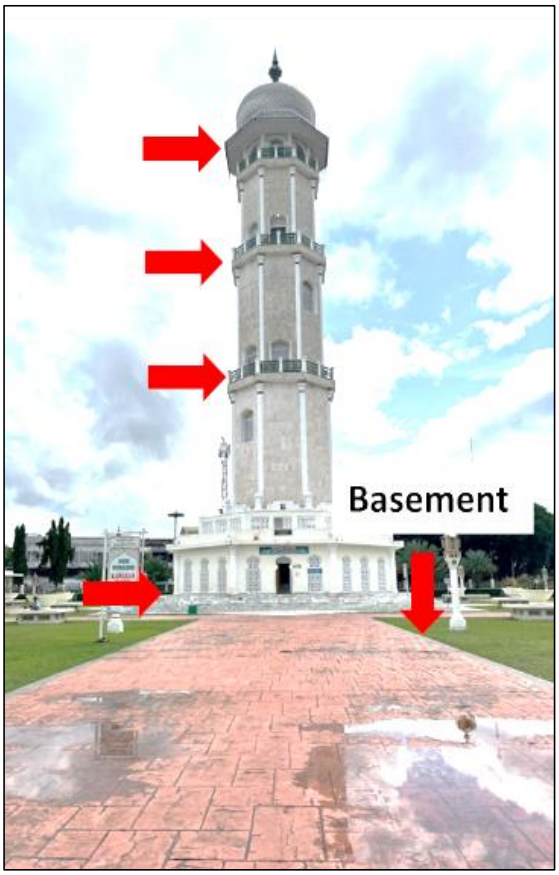


**Fig. 2.** Location of microtremor measurement in the tower of the Baiturrahman mosque.

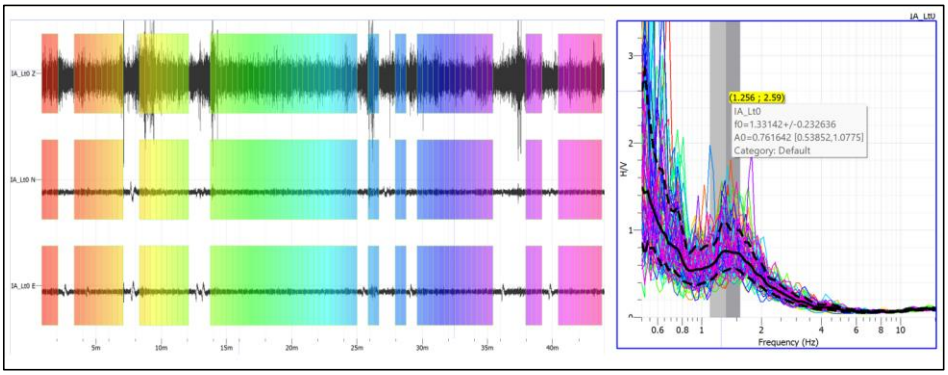


**Fig 3.** Waveform display of microtremor measurement results with windowing (left) and HVSR curve (right) with frequency and amplitude result information in the basement of the Mosque.

### 3.1. Natural Frequency on Each Floor of Tower

RDM analysis is carried out by analyzing the response of the building system to random vibration data to obtain the natural frequency value and damping ratio. The filtered signal results are then segmented with a length of 10 seconds and the average value is taken as the RDM signal. The natural frequency value is obtained by calculating the average time difference between the peaks of the RDM signal. The results of the RDM signal on the NS and EW components of each floor as shown in Figure 4.

Based on Table 1, the natural frequency value of the tower is in the range of 1.18 - 4.32 Hz for the NS component and 1.16 - 4.3 Hz for the EW component. There is no significant difference from the results of the two components. The highest frequency values are found on Floor 2 while the lowest are on Floors 4 and 3. In general, there is a decrease in natural frequency values with increasing building floors in both components.

### 3.2 Resonance the Tower of Mosque

Figure 5 also shows a negative linear correlation between the natural frequencies. The correlation between natural frequency and building height has an R-squared value (coefficient of determination) of 0.4722 and 0.5643 for the NS and EW components, respectively. Table 1 shows the percentage of resonance in the main tower building in the range of 11.16 - 239%. Overall, each building is in a stable condition against the threat of resonance when shaking occurs except on Floors 3 and 4 of the Tower. Floors 3 and 4 in the Main Tower have resonance values ranging from 11-12% in the NS or EW components which are included in the hazard category. This is because the natural frequency values of the two floors tend to be identical to the ground frequency values in the basement of the building.

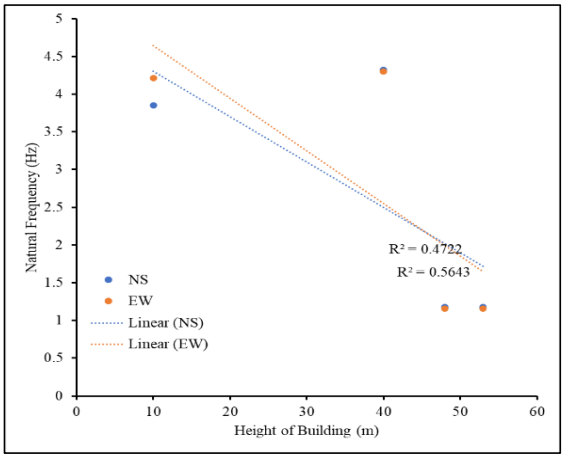


**Fig. 4.** Correlation graph of floor height to natural frequency.

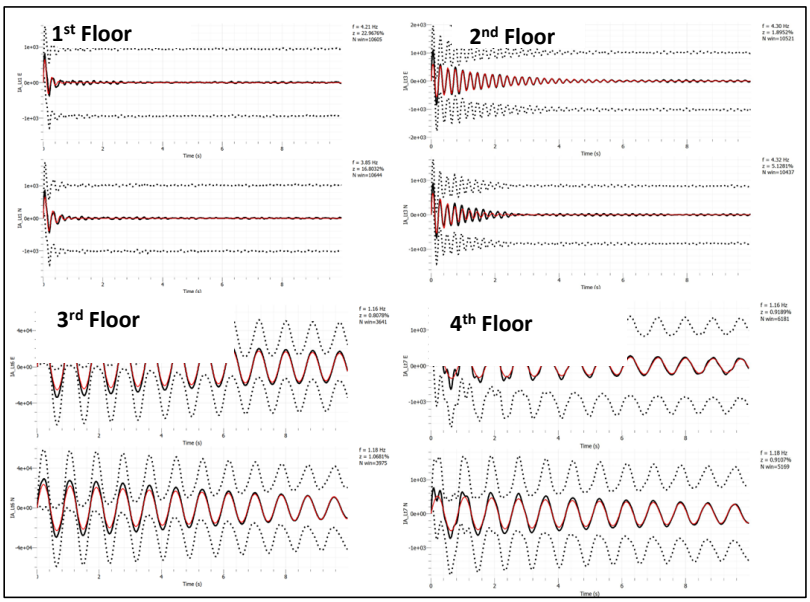


**Fig. 5.** RDM signal from microtremor measurements of each floor at the main tower of the Baiturrahman Grand Mosque. The information of the figure provides RDM signal from microtremor survey for lantai 1 (Floor 1), lantai 2 (Floor 2), lantai 3 (floor 3), and lantai 4 (floor 4).

Table 1. Results of microtremor data processing on each floor of the Baiturrahman Mosque tower.

| Measurement Point | Height Building (m) | Natural Frequency (Hz) | | Damping Ratio (%) | | Resonance (%) | |
|---|---|---|---|---|---|---|---|
| | | NS | EW | NS | EW | NS | EW |
| Story 1 | 10 | 3.85 | 4.21 | 16.8032 | 22.9676 | 189.47368 | 216.54135 |
| Story 2 | 30 | 4.32 | 4.3 | 5.1281 | 1.8952 | 224.81203 | 223.30827 |
| Story 3 | 48 | 1.18 | 1.16 | 0.8078 | 0.8078 | 11.278195 | 12.781955 |
| Story 4 | 53 | 1.18 | 1.16 | 0.9189 | 0.9189 | 11.278195 | 12.781955 |

### 3.3 Damped ratio in Mosque tower

The RDM analysis also produces damping ratio values obtained by measuring the decrease in oscillation amplitude over time with the Logarithmic Decrement method. The results of the damping ratio of each measurement point (Table 1) show that at the Main Tower each floor is in the range of 0.8 - 22.96% for the EW component and 0.9 - 16.8% for the NS component. Damping ratio values that meet the standard are in the range of 3-5% and critical at 8-10%. Thus obtained, Floor 1 has a damping ratio that exceeds the critical limit (overdamped), Floor 2 has a standard damping ratio, and Floors 3 and 4 are below standard. This substandard value can cause the building to oscillate easily when earthquake shocks occur. In general, on the Main Tower, the increasing floor of the damping value decreases along with the decreasing value of the natural frequency.

## Conclusions

The natural and resonant frequency values of the tower show that the ground floor has the highest value, and this value decreases gradually towards the top of the tower. This phenomenon indicates that the upper part of the tower has more flexible structural characteristics and more easily resonates to low-frequency earthquake waves, potentially increasing the dynamic response of the structure. The resonance peak is most clearly detected at the highest floor, indicating that the highest resonance potential exists at that section. This effect is important to consider in the design of vertical structures to avoid harmful resonance effects.

Analysis of the damping levels at each floor and tower shows relatively standard damping values, with values in the range of 0.91 - 22.96%, which fall into the light to medium structural category. These damping values contribute to the high dynamic response of the structure to vibration. Future work with the pushover method and more sophisticated methods in the civilian engineer will explain in more detail that the higher the floor, the lower the damping value tends to decrease, so the top of the tower has the least damping capability and is most susceptible to repeated oscillations during vibration.


## Acknowledgements

The authors would like to express their sincere gratitude to the anonymous reviewers for their constructive comments and valuable suggestions that significantly improved the quality of this manuscript. We are also thankful to the Editor in Chief for the guidance throughout the review process. Special thanks are extended to Dr. Andrean Simanjuntak from BMKG Regional I in Medan for his insightful input and continuous support. We also deeply appreciate the support provided by Afryanti Simangunsong and Rika Adelina Ginting during this study. Finally, we would like to acknowledge Prof. Muksin for his invaluable guidance as the supervisor of this research.


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