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Analysis to Measure Resonance and Building Vulnerability Index in Southern Surabaya, East Java, Indonesia

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Abstract: Microtremor analysis was conducted in southern Surabaya, East Java, to evaluate the seismic response of buildings using the Floor Spectral Ratio (FSR) and Random Decrement Method (RDM). Two buildings—a 9-story structure (Building A) and a 10-story structure (Building B)—were analyzed to assess their dynamic behavior and vulnerability to earthquake-induced shaking. As high-rise building development continues in Surabaya, such assessments are critical for enhancing structural safety. The FSR method provided estimates of natural frequency, amplification, and vulnerability index, while the RDM method determined the damping ratio and validated the natural frequency results. The findings show that the average natural frequency of Building A is 1.18 Hz (North-South) and 1.24 Hz (East-West), while Building B has 1.18 Hz and 1.17 Hz, respectively. Damping ratios ranged from 1 to 4% for Building A and 1 to 6% for Building B, both below the 10% critical threshold. The increasing vulnerability index with height indicates greater susceptibility to seismic amplification at upper floors. These findings confirm that both buildings meet the structural standards for multi-story building, reinforcing the importance of dynamic evaluation in earthquake-prone urban areas.

Keywords: Damping ratio; Microtremor; Natural frequency; Susceptibility index

Introduction

Earthquakes are among the most destructive natural hazards, capable of reducing the strength and stiffness of building structures (Sulonteh & Mahajan, 2024). The design of high-rise buildings is carefully calculated to minimize damage during seismic events, particularly due to the lateral forces they must endure (Shukla, 2023). Surabaya, the second largest city in Indonesia, is currently experiencing rapid physical development, particularly in the construction of high-rise buildings (Aulia et al., 2019; Muqtadir et al., 2024). These buildings are increasingly vulnerable to seismic activity, especially given Surabaya's location near the active Waru and Surabaya fault segments and its underlying soft alluvial soil, which can significantly amplify ground motion (Akbar et al., 2024; Ayi & Bahri, 2012; Gustono et al., 2023; Pamungkas et al., 2019; Syaifuddin et al., 2020).

The resonance that occurs between ground motion and building structures is one of the primary causes of severe damage during earthquakes. Local geological conditions such as soft sediment layers can intensify this effect, particularly in tall buildings. Despite several regional seismic hazard studies, there is a lack of detailed microtremor-based analysis of high-rise buildings in Surabaya. Evaluating the dynamic response of buildings—such as natural frequency, damping ratio, and amplification—is essential for identifying floors with high resonance potential and predicting seismic vulnerability (Akbar et al., 2024; Gallipoli et al., 2020; Rahman et al., 2024; Rohmah et al., 2023).

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This study aims to analyze the dynamic characteristics and seismic vulnerability of two high-rise buildings in southern Surabaya using the Floor Spectral Ratio (FSR) and Random Decrement Method (RDM). FSR is used to determine the natural frequency, amplification, and vulnerability index based on microtremor measurements, while RDM is applied to estimate the damping ratio and validate the frequency data. The novelty of this research lies in the integrated use of these two methods for a comprehensive evaluation of building performance under seismic conditions. The results of this study are expected to contribute to earthquake-resistant building planning and strengthen urban resilience strategies in seismically active regions.

Method

This study employs geophysical measurement techniques using the Floor Spectral Ratio (FSR) and Random Decrement Method (RDM) to analyze the dynamic characteristics of buildings based on microtremor field measurements. The study was conducted on two high-rise buildings in southern Surabaya, referred to as Building A (9 stories) and Building B (10 stories). This region lies near active fault segments such as the Waru and Surabaya faults, and is built on soft alluvial soil, which increases the risk of seismic amplification due to local site effects. These geological conditions make Surabaya particularly vulnerable to earthquake-induced vibrations and resonance, especially in high-rise structures. his study employs geophysical measurement techniques using the Floor Spectral Ratio (FSR) and Random Decrement Method (RDM) to analyze the dynamic characteristics of buildings based on microtremor field measurements. The study was conducted on two high-rise buildings in southern Surabaya, referred to as Building A (9 stories) and Building B (10 stories). This region lies near active fault segments such as the Waru and Surabaya faults, and is built on soft alluvial soil, which increases the risk of seismic amplification due to local site effects. These geological conditions make Surabaya particularly vulnerable to earthquake-induced vibrations and resonance, especially in high-rise structures.

Research Procedure

Microtremor measurements were conducted using a Lunitek portable seismograph (Triton 1s) with three sets of sensors. Sensors were placed simultaneously on each floor of the building and at one reference point on the ground (free-field), located in a stable, horizontal area away from noise sources. Sensor placement near structural corners was chosen to minimize false amplification effects and ensure accurate capture of building vibrations. Each recording lasted approximately one hour and was conducted at night (20:00–04:00 local time) to reduce external noise and environmental interference.

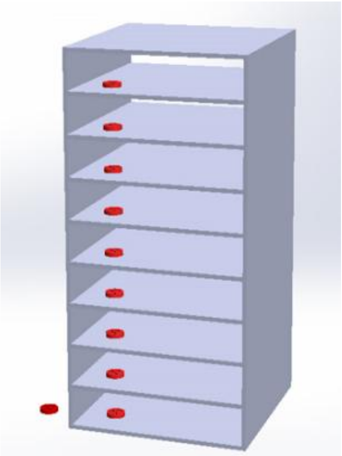

Figure 1. Sensor installation scheme at the corner of the building and reference point

FSR Analysis Method

The recorded microtremor signals were processed using Geopsy software. The recordings were divided into 20–40 second non-overlapping windows for spectral analysis.

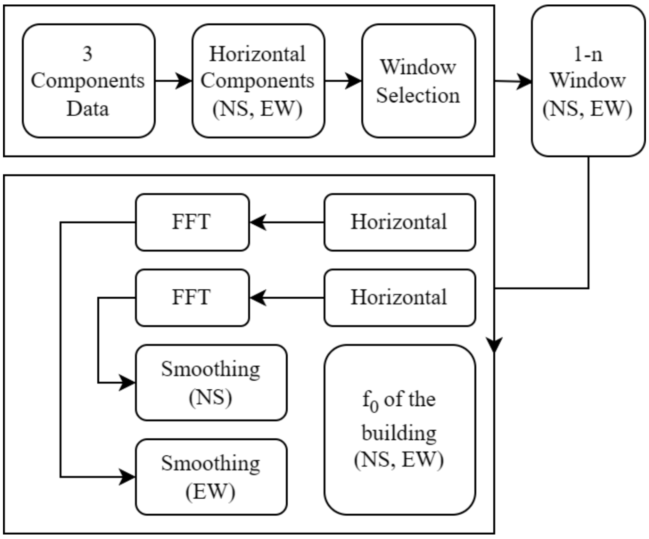

Figure 2. Data processing diagram with FSR method

In spectrum analysis, each recording length was split into 20 to 40-second non-overlapping windows. Konno and Ohmachi smoothing filters with a bandwidth coefficient of 40 seconds were used to smooth the results of the FFT process. The average amplitude spectrum for each component was calculated from the selected window. Furthermore, the natural frequency of the building is obtained by using the FSR analysis, which serves as a spectrum analysis on the measurement of the building floor against the ground beneath it (Sungkono, 2011). Each segment was transformed from the time domain to the frequency domain using a Fast Fourier Transform (FFT), followed by smoothing using the Konno–Ohmachi filter. The FSR method was used to obtain the natural frequency, spectral amplification, and vulnerability index (Kg) by comparing the spectral ratio between each floor and the ground reference point.

RDM Analysis Method

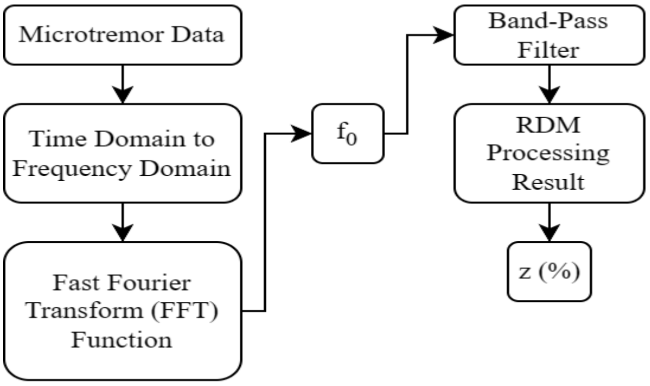

Figure 3. Diagram of the data processing process with the RDM method

The FSR results were used to determine the dominant frequency band for the RDM analysis. A bandpass filter (typically 1–10 Hz) was applied to isolate the relevant frequency range. RDM analysis was performed using the Geopsy Damping Toolbox by averaging multiple free-vibration windows from the microtremor signal. From the resulting decay curve, the damping ratio (ζ) was extracted by analyzing the rate of amplitude reduction over time. The RDM method provides an estimation of the building's energy dissipation capacity and offers a secondary confirmation of the natural frequency obtained through FSR.

Result and Discussion

Based on the processing of microtremor data from Building A and Building B, the following results were found.

Vulnerability Index of Building A

From the measurement results of microtremor in Building A, a comparison of the natural frequency value of the building (f_0), the natural frequency of the ground (f_0), amplification (A_0), and the value of the building vulnerability index (Kg) can be seen in Tables 1 and 2. Table 1 shows that the vulnerability index in both components tends to increase based on the increase in the amplification value from the 1st floor to the 9th floor.

Table 1. Natural frequency, amplification, and vulnerability index of building A

Floor	North - South (N-S)			East - West (E-W)		
	f_0 FSR	A_0	Kg	f_0 FSR	A_0	Kg
1	1.2	1.42	50.01	1.24	2.31	76.19
2	1.23	1.91	106.70	1.24	3.52	193.49
3	1.21	3.03	174.92	1.25	4.88	263.97
4	1.19	5.67	338.41	1.26	5.96	317.30
5	1.17	6.64	409.97	1.24	6.25	343.56
6	1.17	8.05	497.03	1.25	7.45	402.99
7	1.17	6.95	429.11	1.25	8.37	452.76
8	1.16	10.85	681.51	1.25	9.42	509.55
9	1.16	11.99	753.12	1.25	9.98	539.85

Based on the results of the analysis of the building vulnerability index value, the relationship graph of the building vulnerability index on each floor can be seen in Figure 4 as follows.

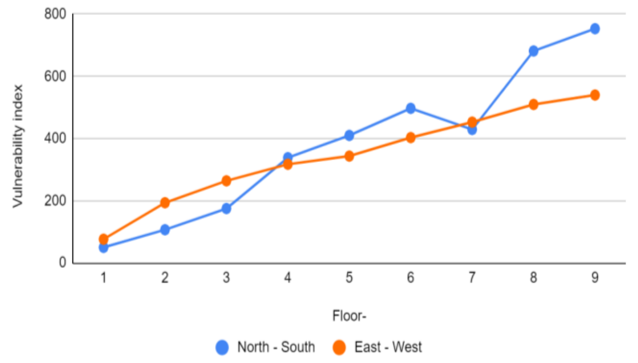

Figure 4. Vulnerability Index Graph of Building A

Figure 4 shows that the building vulnerability index value for the North-South component ranges from 50.0076–753.1173, which has an average vulnerability index value of 382.31, whereas the East-West component ranges from 76.1867–539.8461, which has an average building vulnerability index value of 344.40. The East-West component generally shows a lower vulnerability index value compared to the North-South component.

However, the East-West component demonstrates a more stable trend in the increase of vulnerability index values, indicating a consistent pattern over the observed floors. In contrast, the North-South component exhibits greater variability in its vulnerability index values. A higher level of damage to buildings during an earthquake correlates with a higher building vulnerability index. This correlation suggests that buildings with higher vulnerability indices are more prone to damage during seismic events due to their reduced capacity to dampen vibrations (Dunand, 2002). These findings align with the established use of the vulnerability index in predicting building damage during earthquakes.

Amplification of Building A

Microtremor measurements at Building A obtained an amplification value for each floor as in Table 1 with the graphic depiction as follows.

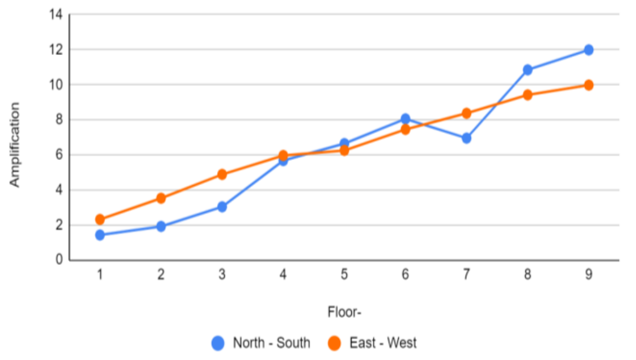

Figure 5. Amplification per floor in Building A

The data indicate a general upward trend in amplification with increasing floor levels for both components. Notably, the North-South component shows greater amplification values compared to the East-West component, particularly at higher floors. This suggests a higher susceptibility to seismic activities in the North-South direction as the building height increases. These results can depict the behavior of the building, where the taller the building, the greater the amplification value. This indicates that the building will experience more shaking in the event of an earthquake.

Resonance of Building A

Microtremor measurements on Building A found a percentage of resonance on each floor. The level of resonance vulnerability of the building to the ground is classified into three criteria according to Gosar (2010) which are high (< ±15%), medium (15–25%), and low (> ± 25%) classes. The results of the resonance research between ground and building are presented in Table 2 as follows.

Table 2. Resonance vulnerability levels of building A floors

Floor	Building f_0 (Hz)		Ground	Resonance %		Classification
	N-S	E-W	f_0 (Hz)	N-S	E-W	
1	1.20	1.24	1.12	20	24	Medium
2	1.23	1.24	1.12	23	24	Medium
3	1.21	1.25	1.12	21	25	Medium
4	1.19	1.26	1.12	19	26	Medium
5	1.17	1.24	1.11	17	24	Medium
6	1.17	1.25	1.11	17	25	Medium
7	1.17	1.25	1.11	17	25	Medium
8	1.16	1.25	1.11	16	25	Medium
9	1.16	1.25	1.05	16	25	Medium

The classification of building vulnerability level, when viewed from the resonance percentage value in Building A, is medium. This is because the building has a natural frequency with a difference that is not too significant with the natural frequency of the ground at the base, as described in Table 2.

Analysis of RDM Method of Building A

The results of microtremor analysis using the RDM method can be seen in Table 3.

Table 3. Results of RDM method analysis of N-S component and E-W component

Floor	f_0 *RDM* (N-S)	*Z*(%)	f_0 *RDM* (E-W)	*Z*(%)
1	1.15	4.40	1.2	3.16
2	1.16	3.00	1.23	2.70
3	1.16	2.37	1.23	2.31
4	1.16	2.26	1.25	2.48
5	1.16	2.11	1.25	2.32
6	1.16	1.77	1.25	2.23
7	1.16	1.67	1.25	2.21
8	1.16	1.71	1.25	2.10
9	1.16	1.42	1.25	1.96

The results of the measurements using the RDM method are the natural frequencies and damping ratios of the North-South component and the East-West component. The damping ratio is the ability of a building to dampen vibration. Thus, physically, the damping ratio increases as the building vulnerability index decreases in the FSR method analysis. Based on the results of microtremor analysis using the RDM method in Building A, the comparison results of the North-South and East-West components are found as shown in Figures 6 and 7.

Based on the comparison of the FSR natural frequency and RDM natural frequency in Figure 6 and Figure 7, the values are almost the same or close; this indicates that the damping ratio generated by the RDM method is accurate, then the amplification factor of the FSR method is also accurate. Furthermore, the amplification factor can be used to calculate the average vulnerability index for building structures.

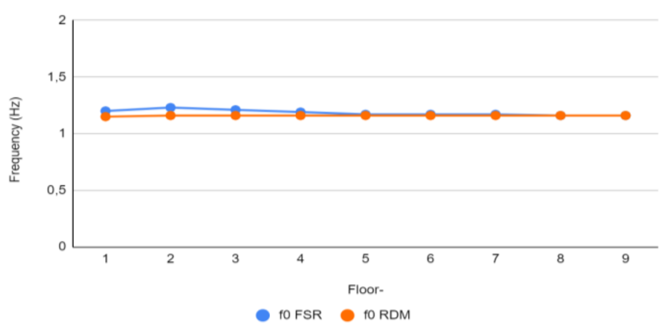

Figure 6. Comparison of Natural Frequency of FSR and RDM in N-S direction

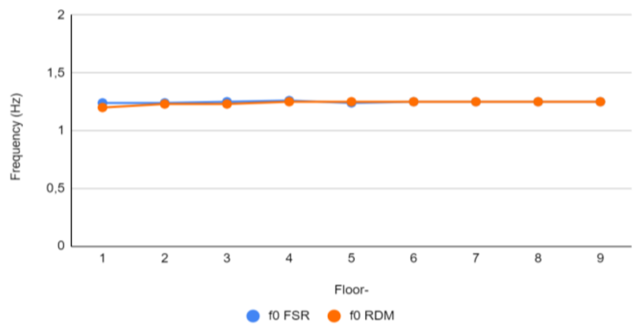

Figure 7. Comparison of Natural Frequency of FSR and RDM in E-W direction

Vulnerability Index of Building B

From the results of microtremor measurements at Building B, a comparison of the natural frequency value of the building, the natural frequency of the ground, the amplification, and the building vulnerability index value can be seen in Table 4.

Table 4 indicates that the vulnerability index in both components of the value tends to increase based on the increase in the amplification value from the 1st floor to the 10th floor in Building B.

Based on the results of the analysis of the building vulnerability index value, we can see the relationship graph of the building vulnerability index on each floor in Figure 8.

Table 4. Results of microtremor analysis of North – South and East – West directions

Floor	North - South (N-S)			East - West (E-W)		
	f_0 FSR	A_0	Kg	f_0 FSR	A_0	Kg
1	1.16	3.47	130.78	1.15	4.11	157.60
2	1.17	3.97	245.12	1.15	6.21	396.87
3	1.16	5.98	375.62	1.15	7.41	473.57
4	1.18	3.85	233.70	1.16	7.12	447.22
5	1.19	4.49	267.99	1.16	8.98	564.05
6	1.20	4.66	273.52	1.16	10.6	665.81
7	1.21	6.89	397.75	1.25	8.83	477.64
8	1.22	8.69	493.47	1.24	11.4	626.64
9	1.22	8.26	469.05	1.16	12.11	760.66
10	1.14	10.59	688.72	1.14	14.13	918.95

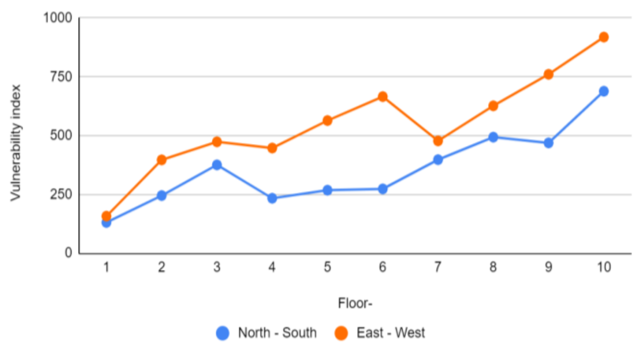

Figure 8. Building Vulnerability Index Graph of Building B

Figure 8 shows that the building vulnerability index value for the North-South component ranges from 130.7748–688.7247, which has an average building vulnerability index value of 357.5703, whereas the East-West component ranges around 157.6002–918.9500 with an average building vulnerability index value of 548.9016. The East-West component has a higher vulnerability index value than the North-South component.

However, the North-South component exhibits a more stable trend in the increase of vulnerability index values, indicating a consistent pattern across the observed floors. In contrast, the East-West component shows greater variability in its vulnerability index values. A higher level of building damage during an earthquake correlates with a higher building vulnerability index (Dunand, 2002). On the 1st floor of both components, the building has the smallest vulnerability index value due to the fact that the hotel lobby is quite tall and spacious and has many connecting room dividers to various rooms.

Amplification of Building B

Microtremor measurements at Building B found an amplification value for each floor, as in Table 4 with the following graphical image which shown in Figure 9. Based on Figure 9, the highest amplification value is in the East-West component located on the 10th floor. These results can help describe how a building moves where the taller the building, the greater the amplification value, indicating that the building feels more shaking when an earthquake occurs.

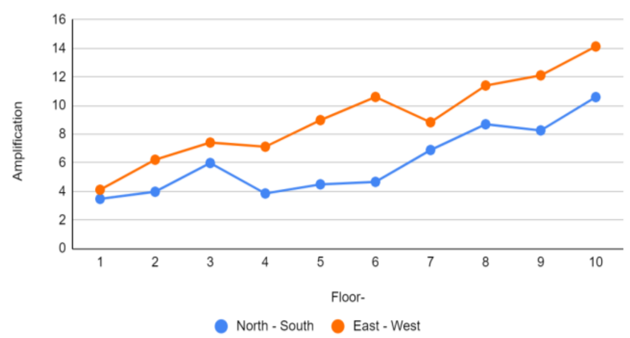

Figure 9. Amplification of each floor in Building B

Resonance of Building B

Microtremor measurements on Building B found the resonance percentage on each floor. The results of resonance research between the ground and the building are presented in Table 5 as follows.

Table 5. Vulnerability level based on resonance percentage

Floor	Building f_0 (Hz)		Ground	Resonance %		Classification
	N-S	E-W	f_0 (Hz)	N-S	E-W	
1	1.16	1.15	1.10	16	15	Medium
2	1.17	1.15	1.10	17	15	Medium
3	1.16	1.15	1.10	16	15	Medium
4	1.18	1.16	1.08	18	16	Medium
5	1.19	1.16	1.08	19	16	Medium
6	1.20	1.16	1.08	20	16	Medium
7	1.21	1.25	1.08	21	25	Medium
8	1.22	1.24	1.08	22	24	Medium
9	1.22	1.16	1.08	22	16	Medium
10	1.14	1.14	1.11	14	14	High

The floor of Building B has a level of vulnerability, with the ground being in the medium to high classification. High vulnerability is found on the 10th floor due to the difference in value between the natural frequency of the building and the ground, which are almost the same. If the natural frequency of the ground is closer to the natural frequency of the building above it, the resonance percentage will be smaller. This means that the level of vulnerability of the building to the ground is higher, and the possibility of resonance between the ground and the building is also increasing.

On the contrary, if the value of the natural frequency of the ground and the building above it has a greater difference in value, the value of the resonance percentage is greater, indicating that the level of vulnerability of the building to the ground is getting lower. The possibility of resonance between the ground and the building is also decreasing (Partono et al., 2013).

Analysis of RDM Method of Building B

The results of microtremor analysis using the RDM method can be seen in Table 6 as follows.

Table 6. Results of RDM method analysis of N-S component and E-W component

Floor	f_0 *RDM* (N-S)	*Z*(%)	f_0 *RDM* (E-W)	*Z*(%)
1	1.15	3.66	1.12	2.13
2	1.15	3.93	1.14	1.75
3	1.15	2.54	1.15	2.60
4	1.16	4.28	1.14	1.95
5	1.16	4.51	1.15	2.04
6	1.16	4.59	1.15	2.19
7	1.18	4.67	1.16	3.68
8	1.18	5.59	1.16	3.26
9	1.19	6.27	1.16	3.09
10	1.19	6.23	1.16	2.07

The damping ratio value is between 1–6%, which meets the standards for the quality of high-rise building structures, where the maximum damping is 10% based on Farsi et al. (2010). The damping ratio generated by the RDM method is dependent on the natural frequency, so to improve the accuracy of the damping ratio, it is necessary to validate the natural frequency of the comparison results using the FSR and RDM methods.

Based on the results of microtremor analysis using the RDM method at Building B in Surabaya, the results of the comparison of the North-South and East-West components are obtained as shown in Figure 10 and Figure 11 as follows.

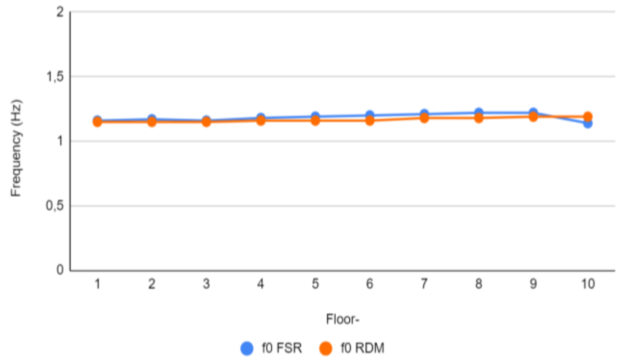

Figure 10. Comparison of Natural Frequency of FSR and RDM in N-S direction

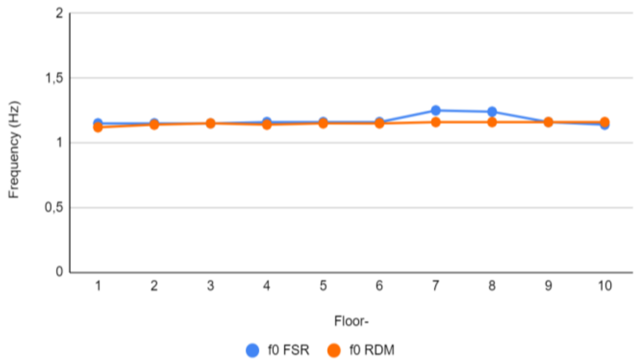

Figure 11. Comparison of Natural Frequency of FSR and RDM in E-W direction

From the comparison of Figure 10 and Figure 11, it is known that the natural frequencies of FSR and RDM in the North-South and East - West components of Building B are relatively close to their natural frequency values, indicating that the resulting damping ratio is accurate.

Conclusion

Building B has a resonance amplification ranging from 14 to 25%. Values in this range fall within the moderate to high category. The 1st to 9th floors are in the moderate class, while the 10th floor shows high amplification. This indicates that the higher the Building B is, the higher the level of vulnerability of the building. Building A shows resonance amplification between 16 and 26%, which also falls within the moderate range.

This indicates moderate susceptibility to resonance effects during seismic activity. As the height increases in Building A and Building B, the building vulnerability index value also increases. In Building A, the damping ratio value ranges from 1 to 4%, and in Building B ranges from 1 to 6%. Although the damping ratios in Buildings A (1–4%) and B (1–6%) are still below the typical critical damping threshold of 10%, lower damping values suggest that these buildings have limited capacity to dissipate seismic energy, making them more vulnerable to prolonged vibrations. The analysis of Building A and Building B shows that the building vulnerability index increases with height. This indicates that taller buildings are more susceptible to damage during earthquakes due to their reduced capacity to dampen vibrations. The results of this research show that the average natural frequency for Building A using the FSR method is 1.18 Hz for the North-South component and 1.24 Hz for the East-West component, while for Building B, it is 1.18 Hz for the North-South component and 1.17 Hz for the East-West component.

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Author Contributions
Conceptualization: A.S.F., A.R., and A.M.; methodology and validation: A.R. and A.M.; formal analysis and data curation: A.S.F. and A.R.; writing-original draft preparation and visualization: A.S.F.; writing-review and editing, and supervision: R.M. and D.A.; resources: R.M., D.A., and M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
No conflicts of interest.

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