

Long-term Monitoring of Low-cost Seismometers: Consistency Analysis of The Instrument

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Abstract – Instruments have become an essential part of conducting a study or research. With the aid of instruments, the measurement process can be faster, more efficient, and more accurate. However, an instrument also has a limited service life. Over time, the performance of the instrument will degrade. Therefore, the equipment must be regularly maintained and calibrated periodically. This research aims to test the measurement consistency of a low-cost seismometer (RS-3D). The approach involves long-term measurements to assess the instrument's stability in taking measurements. The measurement data is then processed and presented as frequencies using spectrum analysis. The research findings indicate that the instrument's consistency is generally good, with an average standard deviation of 0.18 and a coefficient of variation of 5%. Additionally, 95% confidence interval calculations yielded values of 2.52 ± 0.02 for measurements at RKD, 3.04 ± 0.05 for measurements at GLT-USK, and 3.3 ± 0.04 for measurements at GFT-USK. Data validation was performed using the equations from building codes, showing that the difference between the measured microtremor frequency and the empirical equation was less than 1, indicating good measurement results. The conclusion drawn from this study is that a higher standard deviation value indicates a more distributed data spread, signifying less consistent research data. Conversely, a lower standard deviation indicates that the data is more concentrated around the mean value, indicating more consistent measurement results. Moreover, with previous studies having conducted validation and consistency testing, it is hoped that both tests will be routinely performed during instrument maintenance.

Keywords: consistency analysis, low-cost seismometer, RS-3D, confidence interval.

Introduction

Exploration activities using seismic waves have become one of the commonly chosen methods for subsurface surveys or investigations, particularly in seismic investigations and hydrocarbon exploration (Pang *et al.*, 2023). In its application, a seismometer or seismic recorder is an instrument used to record seismic vibrations, whether macroseismic (earthquakes) or microseismic (ambient noise) activities. These recordings are valuable for subsurface investigations or other seismological studies (Yulianur *et al.*, 2020). Various seismic recording instruments have been developed and equipped with various technologies and sensors to enhance their ability

to record earthquake events or ambient noise. Each instrument or sensor has an effective operational lifespan, necessitating regular inspections to ensure the instruments function optimally (Mànuel *et al.*, 2012; Parfitt *et al.*, 2016; Sun *et al.*, 2017; Ekström and Nettles, 2018; Bewley and Pooley, 2022). One method of examining a seismometer is by comparing its measurement results with a calibrated instrument, such as a shaking table. A related study compared the measurement results of the RS-3D seismometer with the MAST system (shaking table). The findings indicated that the RS-3D instrument's recordings were relatively consistent with the results from the MAST system (Setiawan *et al.*, 2022). Another test involved comparing the RS-3D seismometer with the NT20 seismometer. The results showed that, both in laboratory and field tests, the RS-3D seismometer performed very well as an instrument for measuring shallow passive seismic activity (Arosio *et al.*, 2023).

In addition to validation by comparing a seismometer with a calibrated instrument, the instrument can also be tested through long-term recording. This recording process can determine the instrument's uncertainty when making measurements. Based on the results of these recordings, the instrument's level of consistency or reliability in performing measurements can be assessed (Berger *et al.*, 2014; Ringler *et al.*, 2015; Lin *et al.*, 2022; Miao *et al.*, 2023; Pang *et al.*, 2023). A study was conducted using nine types of seismometers. Recordings were made over four months at a station located in Malingshan, China. Self-noise analysis using power spectral density (PSD) was applied, and the results indicated that all nine instruments exhibited stable measurement levels across the low to high-frequency range. However, none of the nine instruments achieved the lowest noise level in all frequency bands within the working range (Wang *et al.*, 2022). Frequency analysis is commonly applied in passive seismic analysis, which is often used to process ambient noise data. Thus, there are two methods for analyzing the stability of a seismometer in recording frequency. The first method is based on the time domain, involving the variance of the frequency fluctuations averaged over time. The second method is based on the spectral domain, involving the spectral density of the phase or the frequency fluctuations (Gros Lambert, Olivier and Uebersfeld, 1974). Spectral density analysis is a preferred method for evaluating an instrument's recording frequency stability. This method allows for comparing horizontal and vertical spectrum measurements and offers easy data processing, making it an advantageous choice for monitoring the instrument's performance degradation (Tian *et al.*, 2012; Koymans *et al.*, 2021). Based on the above discussion, it can be concluded that instrument validation testing can be conducted by comparing the instrument in question with a calibrated instrument. Meanwhile, a seismometer's consistency testing in recording seismic data is performed through long-term measurements. Therefore, this study aims to evaluate the stability of the RS-3D instrument in recording data over an extended period.

Previous Research

The Latest research validated the Raspberry Shake 3D (RS-3D) seismometer instrument by comparing its results with those obtained from a shaking table (Setiawan *et al.*, 2022). The experiment was carried out by performing four iterations. The test results compared the frequency of the MAST System and RS-3D. The results indicate that the measurement obtained with RS-3D closely approximates the value of the MAST System. The measurement results are compared in Figure 1.

The RMSE calculation in this study demonstrates the accuracy of the RS-3D in measuring the input frequency of the shaking table. The calculation yielded an RMSE value of 0.016 g. An RMSE value below 0.1 indicates accurate measurement results, and in this case, the obtained RMSE value is less than 0.1. Additionally, the scatter index (SI) was calculated in this test, yielding an SI value of 2% for the RS-3D instrument. Generally, a SI value below 10% indicates a good instrument, while a SI value below 5% is classified as a perfect instrument. Therefore, the RS-3D instrument is classified as perfect based on its SI value (Setiawan *et al.*, 2022).

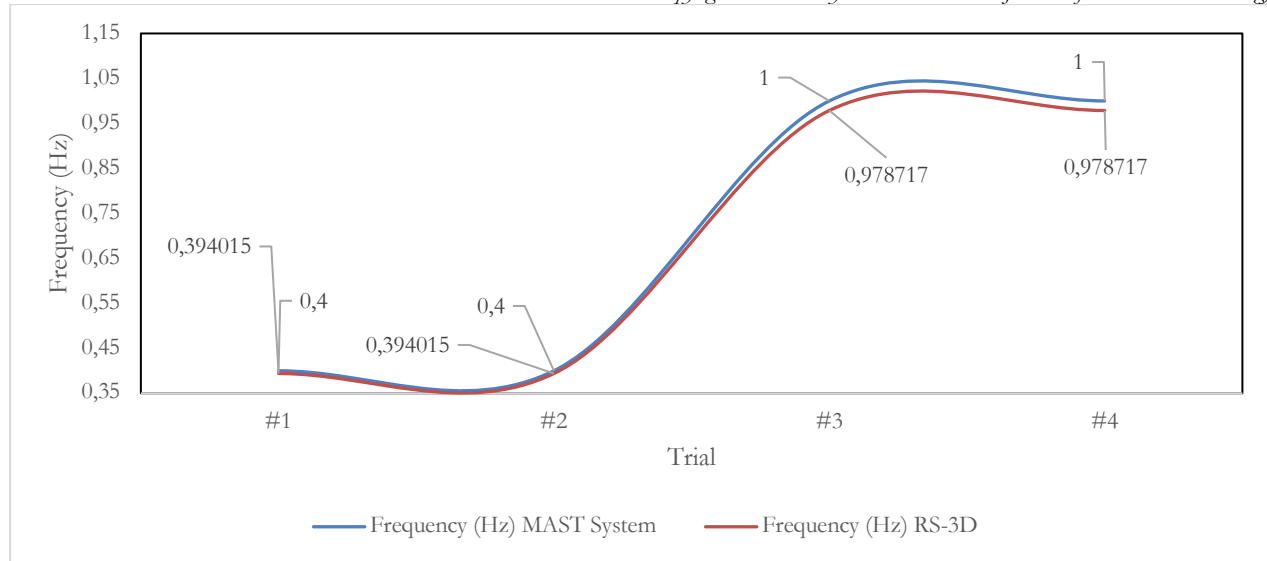


Figure 1. Result of the latest study (modified from Setiawan *et al.*, 2022)

In this study, the testing involved comparing the measurement results of the RS-3D instrument with those of a calibrated shaking table instrument. The test results demonstrated excellent validation. However, aside from validation using a calibrated instrument, another test that can be performed is the consistency testing of the instrument over long-term measurements. This test involves recording data with the instrument over a specific period, which can reveal the consistency of the instrument's recordings over time.

Another test previously conducted on the RS-3D instrument involved comparing it with the NT20 instrument. The main difference between these two instruments is their cost, with the NT20 being significantly more expensive than the RS-3D. The testing was carried out in two phases: laboratory and field. Overall, the laboratory and field test results indicated that the measurement frequency data from the RS-3D ranged from 0.7 to 39 Hz (according to the instrument specifications, the RS-3D can be recorded in the range of 0.5 to 40 Hz). These results show that the RS-3D instrument is highly effective for use in shallow passive seismic applications with low frequency and low amplitude (Arosio *et al.*, 2023).

Materials and Methods

The research utilizes the Raspberry Shake 3D instrument (Figure 2). Testing is conducted by quantifying background noises over a specific period. Measurements were conducted on three buildings, and the specifics of the buildings and the duration of the measurements are provided in Table 1. The object location showed in Figure 3. The measurement results were subsequently partitioned into segments of 30 minutes each. The data analysis was conducted using the spectrum and damping tools available in the Geopsy software. The data obtained consists of the natural frequency data for each object.

The level of consistency is assessed by computing the mean, standard deviation (SD), coefficient of variation (CoV), and 95% confidence interval (95% CI) for each frequency data processing result of each study object. The calculation of standard deviation is performed to ascertain the average level of dispersion of the measurement data (Siegel and Wagner, 2022). In order to assess the variability of measurement data, it is essential to compute the coefficient of variation (CoV). CoV is a measure that compares the variability (standard deviation) of a dataset to its average (mean) (Cottis, 2021). Another statistical test utilized in this research involves the computation of confidence intervals (CI). The commonly utilized confidence interval (CI) value in statistical

analysis is 95% (Lee, In and Lee, 2015). CI testing is carried out to find out how confident it is that the frequency calculation results will get a specific value from the population if sampling is carried out repeatedly. A CI's primary function is to estimate the range of values that a population parameter may contain with a certain level of confidence (Lee, In and Lee, 2015; Loftus, 2022).

The measured frequency values are verified by comparing them with those calculated using equations derived from the building code. The equation proposed in ASCE 7-16, also adopted in SNI 1726, is frequently used to calculate the structural period (American Society of Civil Engineers, 2017; Badan Standardisasi Nasional, 2019). Mathematically, the equation can be written as follows:

$$T = T_a = C_t h_n^x$$

The height of the building in metric units, denoted as h_n , is determined according to the guidelines provided in section 11.2 of ASCE/SEI 7-16. Coefficients C_t and x are used to calculate the period of the structure in metric units, which can be found in Table 3.

Table 1. Instrument testing location

Building	Location	Floor	Measurement duration (hour)
Rusunawa Keudah Blok D (RKD)	Rama Setia St, Merduati, Kuta Raja, Banda Aceh	4	52
Gedung Fakultas Teknik-USK (GFT-USK)	Syekh Abdurauf St No.7, Kopelma Darussalam, Syiah Kuala, Banda Aceh	1	72
		2	
		3	
Gedung Laboratorium Terpadu USK (GLT-USK)	Syekh Abdurrauf St No.10, Kopelma Darussalam, Syiah Kuala, Banda Aceh	1	4
		2	
		3	

Table 2. Coefficient value of x and C_t (American Society of Civil Engineers, 2017; Badan Standardisasi Nasional, 2019)

Structure type	C_t	x
Steel moment-resisting frames	0.0724	0.8
Concrete moment-resisting frame	0.0466	0.9
Steel eccentrically braced frame	0.0731	0.75
Steel buckling restrained braced frames	0.0731	0.75
All other structural system	0.0448	0.75

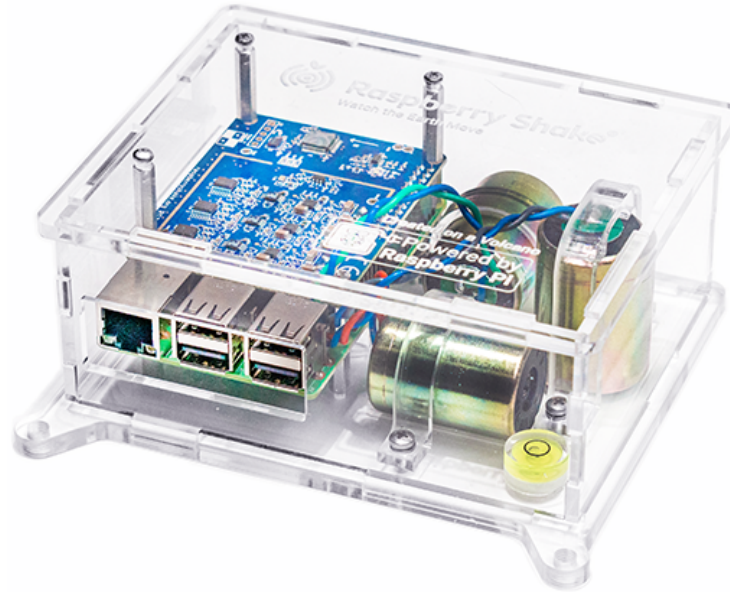


Figure 2. Raspberry Shake 3D (Raspberry Shake, 2023)

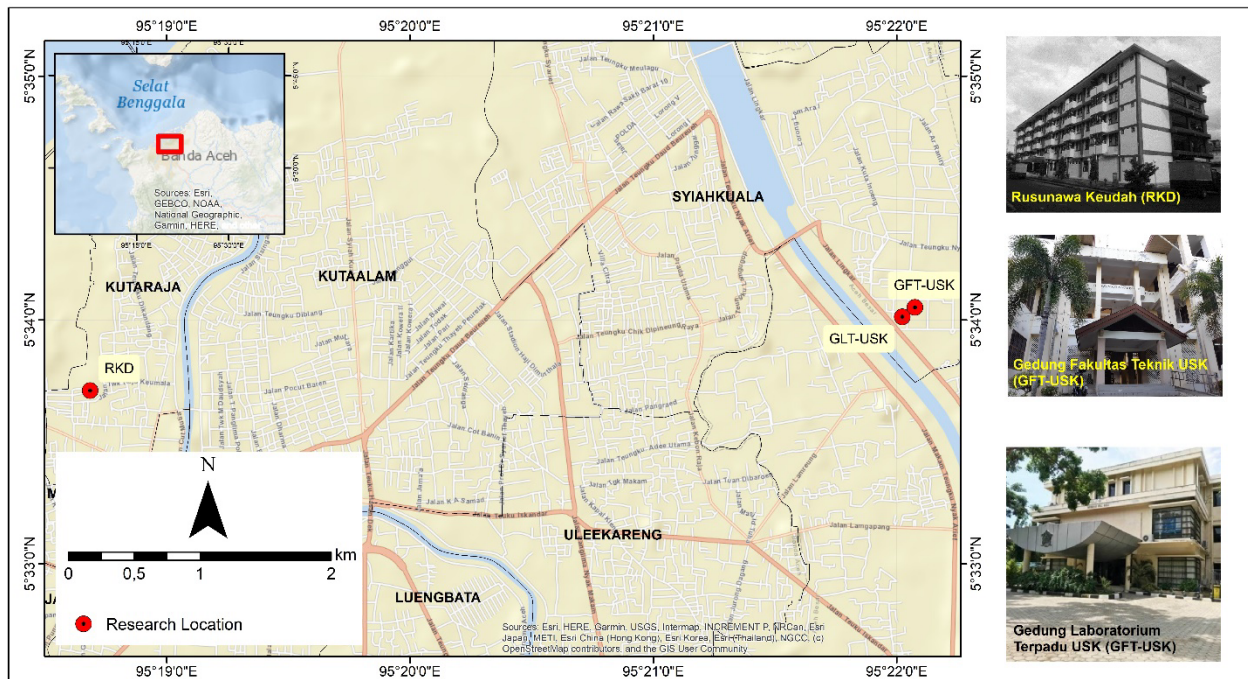


Figure 3. Research Location

Furthermore, the fundamental period can be determined using the following method:

$$T = T_b = 0,1 N$$

This condition applies only when the number of floors in the building, represented by N, is less than 12 and the building has a fully constructed concrete or steel frame. Additionally, each floor must have

an average height of at least 3m (American Society of Civil Engineers, 2017; Badan Standardisasi Nasional, 2019). Another equation that can be adopted to measure the base period of a building is stated in the EC-8 building code (CEN and Eurocode 8, 2004). The equation is written as follows:

$$T = T_c = \frac{0,09 h_t}{L^{0,5}}$$

Where h_t is the height of the building, while L is the width of the building in the direction of the acting force, the natural frequency of the structure can be calculated by dividing the period value of the structure that has been obtained. This value can be used to compare and validate frequency results from consistency testing.

Consistency testing was performed by calculating the mean, standard deviation (SD), coefficient of variation (CoV), and 95% confidence interval (95% CI) for each set of frequency data from the study objects. Calculating the standard deviation determined the degree of distribution around the mean of the measurement data (Siegel and Wagner, 2022). The coefficient of variation (CoV), which is the ratio of the standard deviation to the mean, needs to be calculated to determine the high or low degree of distribution around the mean of measurement data (Cottis, 2021). Another statistical test applied in this study is the confidence interval (CI) calculation. The commonly used CI value in statistical analysis is 95% (Lee, In and Lee, 2015). The CI test determines how confident we can be that the frequency calculation results will fall within a certain value range from the population if sampling is repeated multiple times. The primary function of the CI is to provide an estimated range of values that likely contain the population parameter with a certain level of confidence (Lee, In and Lee, 2015; Loftus, 2022).

Results

Spectrum and damping analysis

The initial measurement was conducted on the Rusunawa Keudah (RKD) building, lasting 52 hours. This building is located on Rama Setia Street, Kutaraja District, Banda Aceh, Aceh, Indonesia. A total of 104 data segments were obtained. The data analysis findings are displayed in Figure 4. The displayed data represents the natural frequencies obtained using damping tools and spectrum analysis in two horizontal directions: East-West (EW) and North-South (NS).

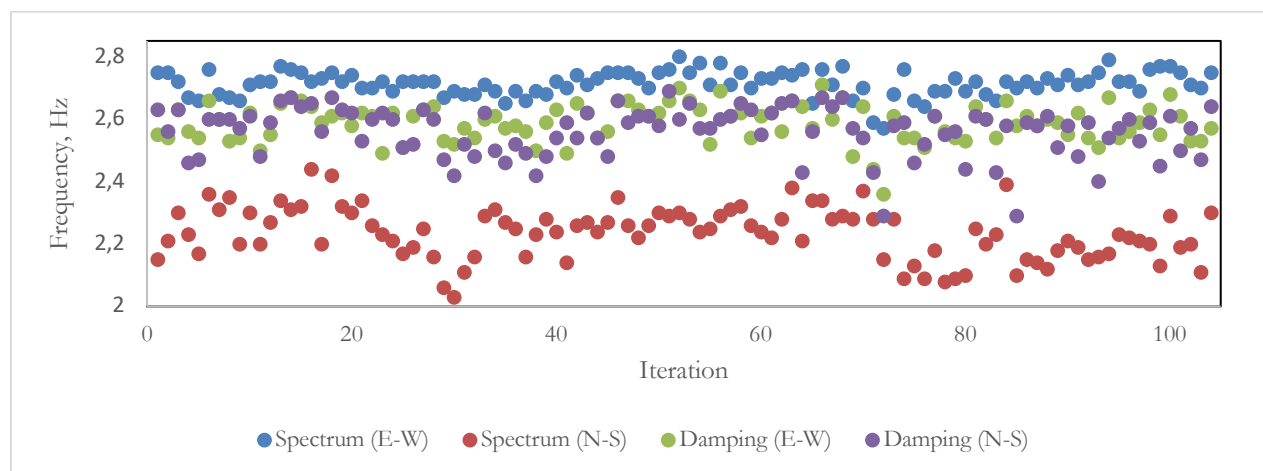
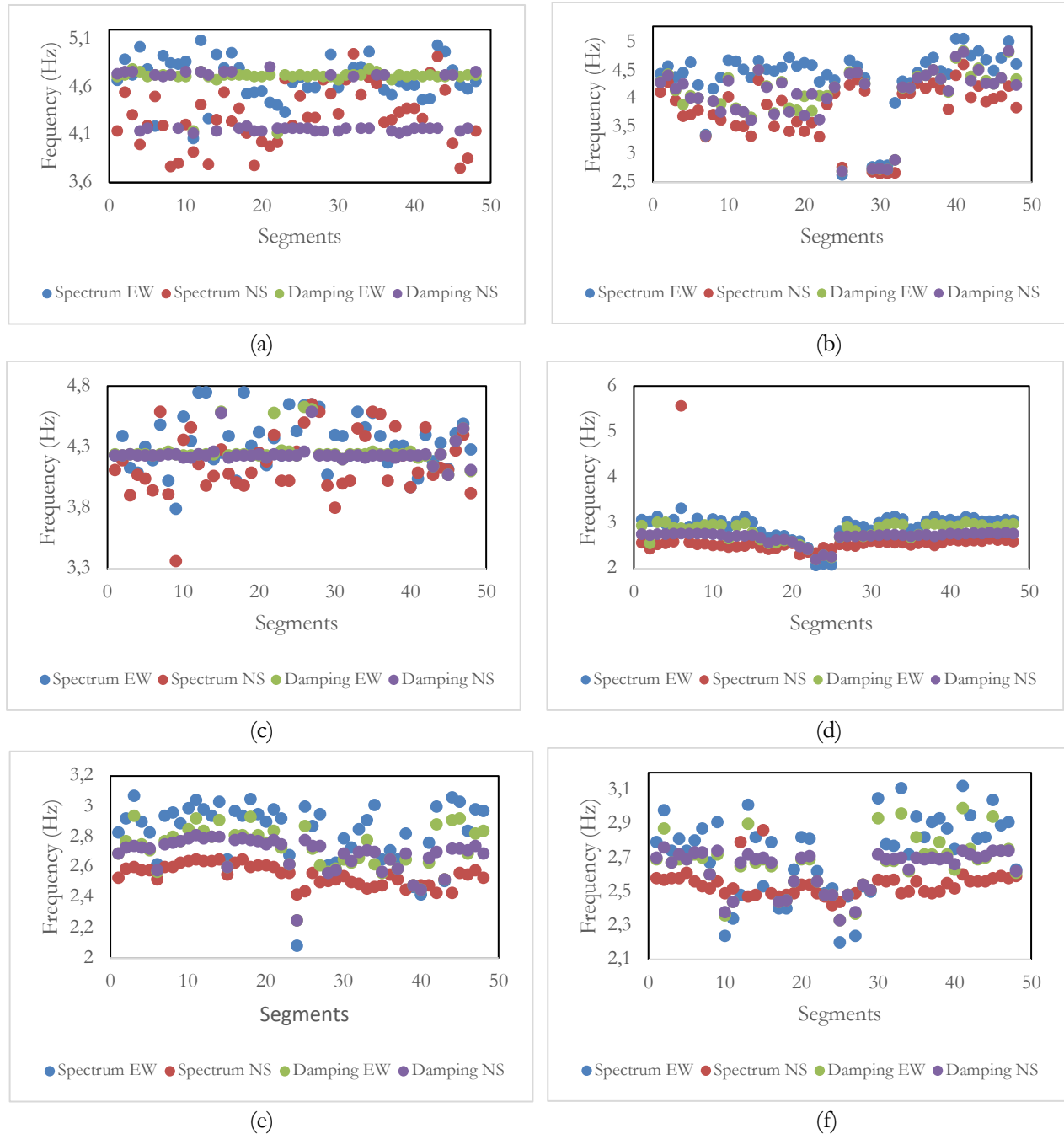


Figure 4. RKD frequency result analysis

The second measurement was done at the GFT-USK, the Gedung Fakultas Teknik Universitas Syiah Kuala. The building is located on Syekh Abdurauf Street, Kopelma Darussalam, Syiah Kuala District, Banda Aceh, Aceh, Indonesia. The measurement was conducted at three locations on every floor. The total number of

measurement points was 9. The measurement duration lasted for 24 hours at each point, yielding 48 segments at each point. Figure 5 displays the damping and spectrum analysis outcomes conducted on GFT-USK.



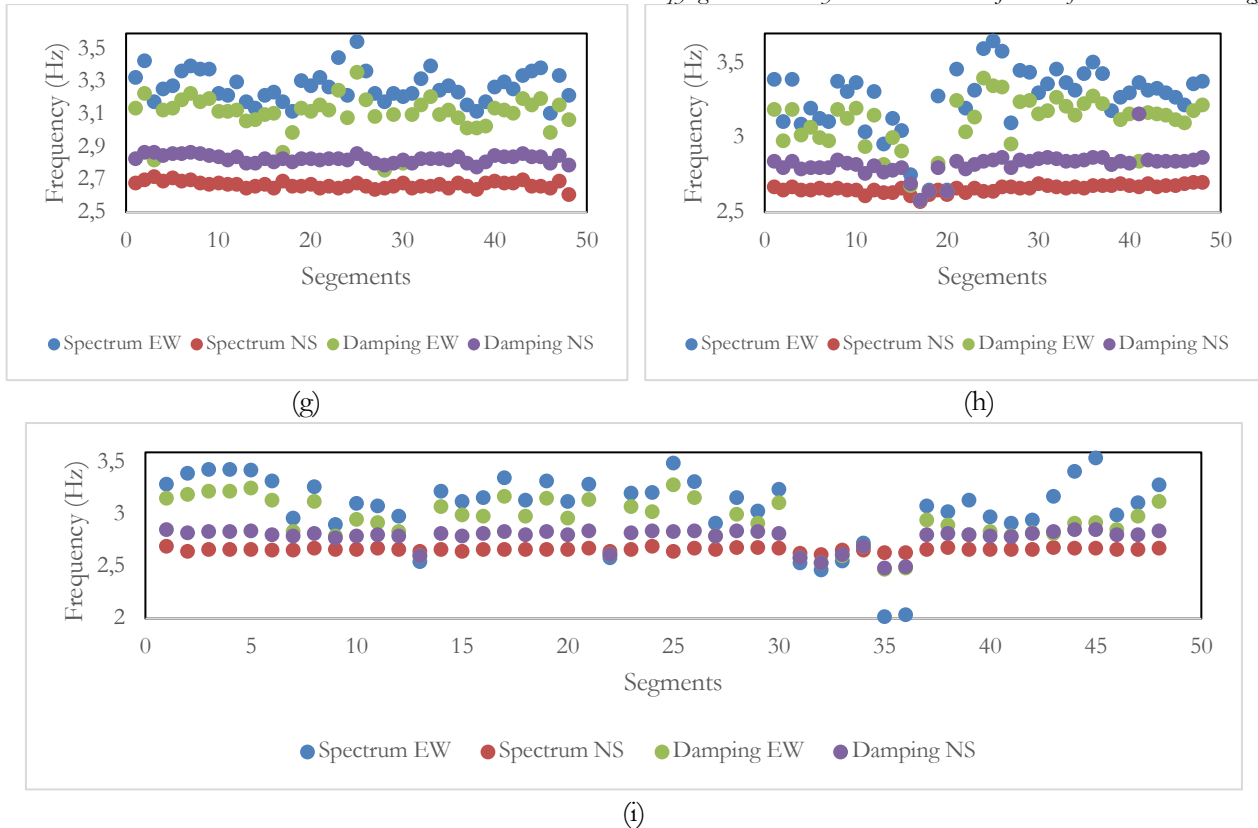


Figure 5. GFT-USK frequency result analysis, (a) 1st Floor Point A, (b) 1st Point B, (c) 1st Floor Point C, (d) 2nd Floor Point A, (e) 2nd Point B, (f) 2nd Floor Point C, (g) 3rd Floor Point A, (h) 3rd Point B, (i) 3rd Floor Point C

The most recent measurement was conducted at the GLT-USK, the Gedung Laboratorium Terpadu Universitas Syiah Kuala. The building is located on Syekh Abdurauf Street, Kopelma Darussalam, Syiah Kuala District, Banda Aceh, Aceh, Indonesia. The measurement was conducted at the central location of each floor, which has three floors. The measurement duration lasted for 4 hours, resulting in the acquisition of 8 data segments on each floor. Figure 6 displays the outcomes of the damping and spectrum analysis.

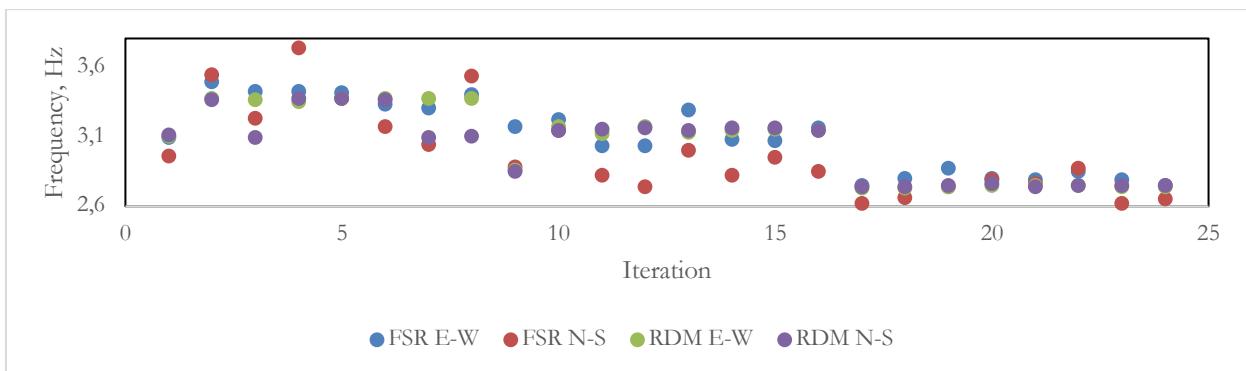


Figure 6. Frequency analysis result on GLT-USK

The instrument's consistency level is assessed by calculating each measurement data's standard deviation and coefficient of variation. The calculation is performed at each measurement point. The computation outcomes are displayed in Table 3. The 95% confidence interval is calculated for each measurement result. The computation is displayed in Table 4. The result is validated by computing the building period value using the equation specified in the building code. Subsequently, the value is transformed into a frequency value to facilitate comparison with the outcomes of the consistency test. Table 5 displays the outcomes of the structural period calculation using the building code and the comparison of frequencies between the building code calculation results and the microtremor measurements.

Discussion

Microtremor measurements were conducted at RKD on the 4th floor in room 414 (Figure 7). The measurement duration was 52 hours, and the collected data was subsequently processed using geopsy software. The frequency values were determined using the damping tool or spectrum in both the NS and EW orientations, ranging from 2.03 to 2.8 Hz. The standard deviation calculation revealed that the NS direction damping analysis and NS direction spectrum had the highest value of 0.08. In contrast, the lowest standard deviation value of 0.04 was observed in the EW direction spectrum analysis. The coefficient of variation was calculated for the NS and EW direction spectra. The NS direction spectrum had the highest value of 4%, while the EW direction spectrum had the lowest value of 1%.

Table 3. Standard deviation and coefficient of variation

Table 3: Summary of observed and calculated coefficients of variation														
Buidling	Floor	Location	Mean				Standard Deviation				Coefficient of Variation			
			Damping		Spectrum		Damping		Spectrum		Damping		Spectrum	
			NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW
RKD	4	414	2.56	2.59	2.23	2.72	0.08	0.06	0.08	0.04	3%	2%	4%	1%
GLT-USK	1	A	2.75	2.74	2.71	2.80	0.01	0.01	0.08	0.04	0%	0%	3%	1%
	2	B	3.11	3.11	2.90	3.13	0.10	0.10	0.12	0.09	3%	3%	4%	3%
	3	C	3.23	3.33	3.32	3.36	0.13	0.09	0.25	0.11	4%	3%	8%	3%
		A	4.39	4.70	4.29	4.69	0.29	0.12	0.30	0.22	7%	3%	7%	5%
GFT-USK	1	B	4.03	4.04	3.79	4.38	0.54	0.53	0.49	0.56	13%	13%	13%	13%
		C	4.24	4.27	4.17	4.34	0.09	0.11	0.25	0.22	2%	3%	6%	5%
		D	4.24	4.27	4.17	4.34	0.09	0.11	0.25	0.22	2%	3%	6%	5%
	2	E	2.69	2.80	2.59	2.92	0.13	0.21	0.44	0.27	5%	8%	17%	9%
		F	2.69	2.72	2.55	2.84	0.11	0.14	0.07	0.20	4%	5%	3%	7%
		G	2.64	2.66	2.54	2.73	0.11	0.15	0.07	0.23	4%	6%	3%	8%
	3	H	2.82	3.08	2.66	3.25	0.08	0.19	0.03	0.23	3%	6%	1%	7%
		I	2.78	2.94	2.67	3.07	0.10	0.21	0.02	0.34	3%	7%	1%	11%
Mean							0.14	0.16	0.9	0.21	4%	5%	6%	6%

Table 4. 95% Confidence interval

Building	N	SD	$\bar{X}$	SEM	95% CI
RKD	416	0.19	2.52	0.009	2.52±0.02
GLT	96	0.26	3.04	0.052	3.04±0.05
GFT	1728	0.77	3.3	0.036	3.3±0.04

Table 5. Comparative analysis of microtremor measurement results with building code frequency standards

Building	T _{code} (s)	F _{code} (Hz)	Spectrum (Hz)	Damping (Hz)
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	Ta	Tb	Tc	fa	fb	fc	f _{NS}	f _{EW}	f _{NS}	f _{EW}
RKD	0.54	0.5	0.17	1.85	2	5.88	2.23	2.72	2.56	2.59
GLT	0.56	0.3	0.21	1.79	3.33	4.76	3.32	3.36	3.23	3.33
GFT	0.51	0.3	0.24	1.96	3.33	4.17	2.66	3.25	2.82	3.08

Microtremor measurements were conducted on GLT-USK at the central location of each floor (Figure 8a). The duration of each measurement at each point was 4 hours. The analysis yielded the frequency value using the damping tool or spectrum in both the NS and EW directions, falling within the 2.62-3.73 Hz range. The standard deviation calculation revealed that the NS direction spectrum analysis on the 3rd floor had the highest value of 0.25. Conversely, the lowest standard deviation value of 0.01 was observed in the EW and NS direction damping analysis on the 1st floor. The coefficient of variation was highest at 8% for the NS direction spectrum analysis on the 3rd floor. In comparison, the lowest value of 0% was obtained for the EW and NS direction damping analysis.

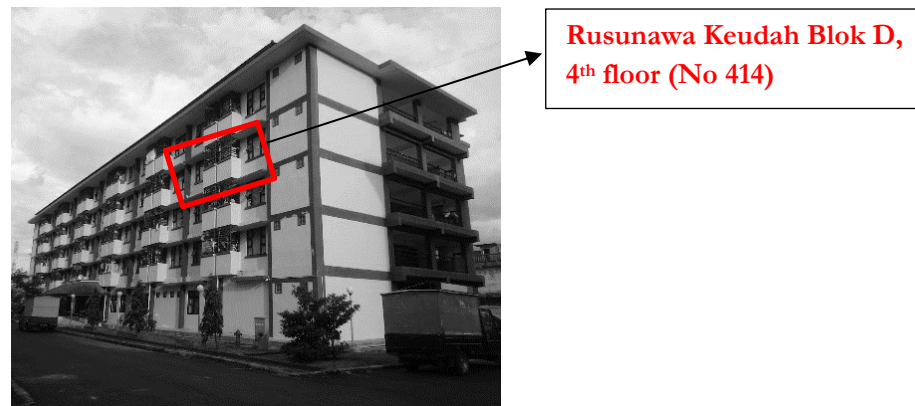


Figure 7. Data collection location (RKD)



Figure 8. Data collection location, (a) GLT-USK, (b) GFT-USK

Microtremor measurements were conducted at GFT-USK on every floor at three locations per floor (Figure 8b). Each measurement lasted for 24 hours at each location. The analysis yielded frequency values for each floor, obtained using the damping tool or spectrum, in both NS and EW orientations. The frequency ranges for floors 1 to 3 were 2.63-5.09 Hz, 2.07-5.56 Hz, and 2.02-3.65 Hz, respectively. The calculation of standard deviation on

all floors revealed that the highest value was obtained in the EW direction spectrum analysis results at point B on the 1st floor, with a value of 0.56. Conversely, the lowest standard deviation value was found in the NS direction spectrum analysis results at point I on the 3rd floor, with a value of 0.02. The coefficient of variation was calculated for the NS direction spectrum analysis at different points on different floors. The highest value of 17% was obtained at point E on the 2nd floor, while the lowest 1% was obtained at points H and I on the 3rd floor.

As the standard deviation value increases, the data becomes more dispersed. However, for this research, the anticipated outcome is minimal data dispersion. Thus, it is desired that the obtained standard deviation value is low. Calculations for the Coefficient of Variation (CoV) are necessary to determine whether the standard deviation values are high or low. The coefficient of variation (CoV) is considered low when it falls within a range of less than 30%, indicating that the data is reasonably homogeneous. Conversely, the data is classified as heterogeneous if the CoV value exceeds 30% (Fávero and Belfiore, 2019). The average standard deviation value obtained from all measurement data is 0.18, with a coefficient of variation value of 5%. This indicates that from all the data from the analysis, the level of data distribution is 0.18 of the mean value obtained with a variation level of 5%. From these data, it can be concluded that the standard deviation level of the measurement data is classified as low and consistent; this is because the CoV value obtained is less than 30% (only 5%), so the data from testing the consistency level of the Raspberry Shake 3D instrument on the three study objects is classified as consistent. And very good. Another statistical analysis was carried out by calculating confidence intervals. The confidence interval (CI) value is a range of values calculated from statistical data, which shows how confident it is to obtain estimates of specific parameters from the population if sampling is carried out repeatedly. The primary use of the confidence interval value is to provide an estimate of the range or range of values that may contain a population parameter with a certain level of confidence (Lee, In and Lee, 2015; Loftus, 2022). The 95% confidence interval value is a limit commonly used in analysis (Lee, In and Lee, 2015). The CI value obtained for each measurement result is displayed in Table 4, based on the measurement results data. The confidence interval indicates a 95% certainty that the actual population average falls within the range of values obtained from repeated measurements. Nevertheless, this outcome is merely a statistical approximation. To illustrate this, let us examine the measurement results of the GFT Building, which encompass a total of 1728 data points. By applying the 95% confidence interval calculation, we find that 1641 data points fall within the range of 3.3 ± 0.04 .

Table 5 demonstrates that the outcomes of structural frequency calculations, specifically f_a and f_b , based on equations derived from the building code, exhibit a considerable degree of similarity when compared to measurements obtained from microtremors. The discrepancy between the numbers obtained for f_a and f_b is less than 1. Nevertheless, there is a significant disparity in the results obtained for the equation from EC-8. Nevertheless, the calculation based on the building code is only partially objective, as it is influenced by various factors, including the structural geometry factor, contributing to the bias. Nevertheless, the equations specified in the building code have been systematized and are extensively employed in structural design. Thus, according to the comparison results, the frequency values obtained from the microtremor measurements are relatively similar to those calculated using the building code.

Conclusion

Based on the research results above, the following conclusions can be drawn:

1. Affordable instruments have emerged as a viable alternative for specific studies or research. Nevertheless, it is essential to consistently monitor and calibrate the instruments to ensure the obtained data is highly accurate and precise. According to the statistical analysis results, which involved calculating

the standard deviation, coefficient of variation, and confidence interval, it can be concluded that the instrument's consistency level is both consistent and stable. This is related to data dispersion could be more widely distributed from the average measurement outcomes. In addition to being determined by the data distribution, the coefficient of variation, the ratio of the standard deviation to the mean, is also relatively low, specifically less than 30%. Furthermore, the validation results obtained using equations derived from the building code exhibit a high degree of similarity to those obtained from microtremor measurements. Overall, the instrument demonstrates high consistency and accuracy in measuring data.

2. This study has a limited scope, focusing solely on testing the instrument's consistency by measuring microtremors over an extended period. Previous research has attempted to validate the results using a shaking table instrument. It is hoped that future research can expand on this by comparing the measurement results between two or more instruments to determine the extent of the differences in their measurements. Also, self-noise testing and testing by applicable standards should be implemented to ensure that the instruments used remain well-calibrated.

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