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Microtremor analysis to evaluate BMKG region III building, Bali, Indonesia

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Abstract

Bali Island has experienced more than 6 significant earthquakes (magnitude > 6) since 1815, which caused extensive damage to buildings and casualties. The microtremor data analysis in the building of Indonesian meteorology, climatology and geophysics agency (BMKG) Region III Denpasar aims to reduce the risk of building damage and casualties due to the earthquake. The analysis was conducted by measuring microtremor and processing the data to obtain the natural frequency of the soil (f_0s HVSR) and building (f_0b HVSR), resonance, soil (*Kg*), and building vulnerability index (*Kb*) so that the safety of the building can be known in the event of an earthquake. The processing and analyzing results the characteristics of microtremor data get the f_0b has a greater value than the f_0s value so that the building is relatively safe from resonance. The resonance value of the building with the ground has an (*R*) value of 6.67% - 13.3%, with an average resonance value of 8.89% which is included in the medium resonance. The location of the building is in an area with a *Kg* of 8.20 – 10.81, which is included in the category of low to moderate soil vulnerability index, and the *Kb* has a value of 0.4827×10^{-6} – 7.9771×10^{-6}, with the first floor having an index highest vulnerability. The f_0s, f_0b, *R*, *Kg*, and *Kb* show that the building is in the safe category in the event of an earthquake.

Keywords: *Microtremor, Natural frequency, Resonance, Vulnerability building, Bali*

1. Introduction

Bali, which is located in a subduction zone between the Indo-Australian Plate and the Eurasian plate, and the presence of Back Arc Trust tectonic activity in the north, causes a high potential for earthquakes (Daryono 2011). Historical records show that some large earthquakes with a magnitude > 6 on the Richter Scale caused massive loss of life and damage in 1815, 1857, 1917, 1976, 2011, and 2019 (Maharani 2020).Earthquakes cause shaking and shaking of the building structure, which can cause damage to the building. Therefore, designing a building is necessary to consider the factors that can damage the structure of the building due to an earthquake. A safe and earthquake-resistant building is a building that meets SNI 1726:2002 (Wangsadinata 2002) concerning procedures for planning earthquake resistance. In addition, the building also has a natural frequency that is greater than the natural frequency of the soil. The value of the resonance index and the value of the vulnerability of the building is small (Gosar 2007). The natural frequency value can be influenced by its size, shape, and composition (Nakamura 2000).

The BMKG Region III building is located in Kuta city, Bali. That building geologically in the Quaternary alluvium Formation with gravel to gravel sand texture, silt, and clay which is the product of the river, lake, and beach deposits (Fig 1) (Hadiwidjojo et al. 1998).

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The location of the BMKG Region III Bali building has a small amplification and dominant frequency, with a large seismic vulnerability index and a significant ground shear strain value so that the research location has a high potential for damage (Kurniawan et al. 2017). However, research has not been conducted on building resonance and building vulnerability index, especially the BMKG Region III Denpasar building.

From a geological point of view, if an earthquake occurs, the BMKG Region III building in Bali is in an area with a high potential for damage. So that in this study, measurements and processing of microtremor data will be carried out to obtain building safety values. The natural frequency value on the soil is carried out by processing microtremor data using the horizontal to vertical spectral ratio method (Konno and Ohmachi 1998; Gallipoli et al. 2004; Över et al. 2011; Abdialim et al. 2021)). Whereas the natural frequency value in the building is determined using the floor spectral ratio method and the analysis spectrum results from each floor to the ground below it to get the natural frequency building value (Gosar 2007; Triwulan et al. 2010; Prakosa et al. 2015).The results obtained from processing the two methods are natural frequency values, but resonance and amplification values will be obtained. The building resonance value is determined based on the spectrum for each component (NS and EW). Resonance can be used to determine the level of possibility of a building experiencing resonance during an earthquake (Gosar et al. 2010).

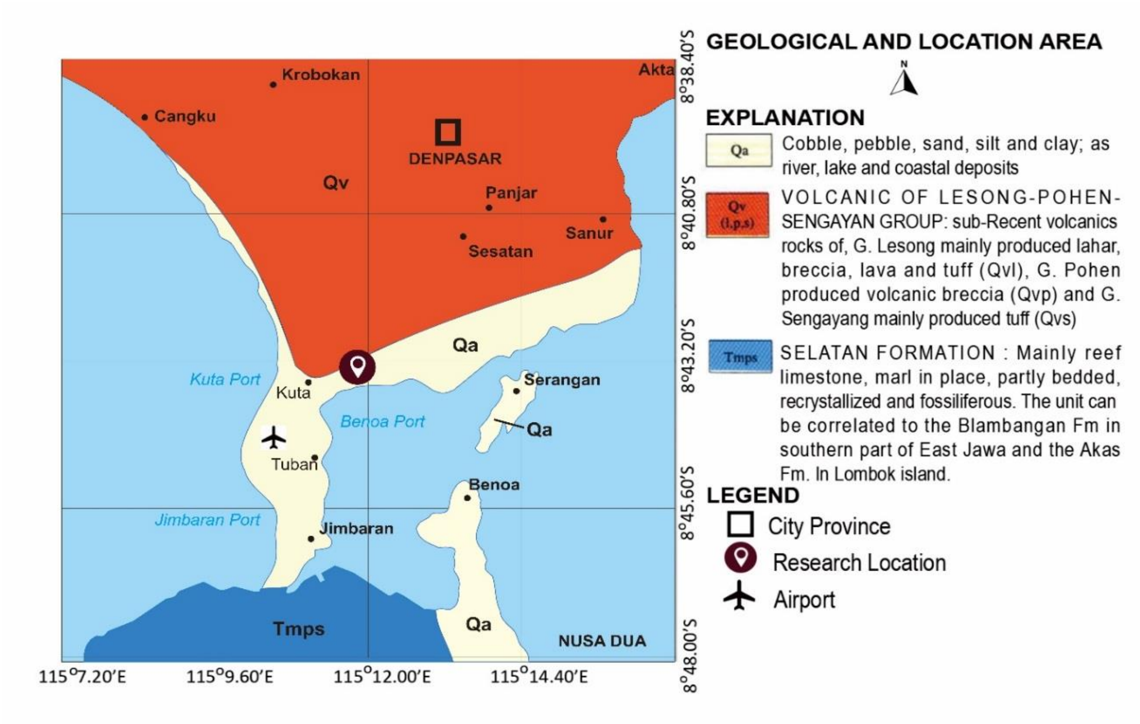

Fig 1. Geological map and location of the research area (modified from Hadiwidjojo et al. (1998)).

The value of the amplification and natural frequency in soil and buildings can be used for further analysis to obtain the value of soil vulnerability analysis (Büyüksaraç et al. 2013; Bekler et al. 2019), building vulnerability analysis, and building resonance. The level of building damage is directly proportional to the soil vulnerability index (Nakamura 2000).

2. Theory

2.1. Microtremor

Microtremor is a ground vibration that human activities or natural activities can cause. Microtremor can occur due to vibrations caused by walking, car vibrations, engine vibrations, wind vibrations, ocean waves, or natural vibrations from the ground (Tokimatsu 1995). Microtremor has a higher frequency than the frequency of earthquakes, and the period is less than 0.1 seconds which is generally between 0.05 - 2 seconds. It can be 5 seconds for long period microtremors, while the amplitude ranges from 0.1 to 2.0 microns. Microtremor is a ground vibration that propagates in the form of waves called microseismic waves. Recently, microtremor applications have been used to identify the natural resonance frequencies of buildings and soils (Gallipoli et al. 2004; Gosar 2007; Gosar et al. 2010).

Microtremor can be used to design earthquake-resistant buildings by knowing the natural period of the local soil to avoid resonance. The measured microtremor data consists of 3 components, namely: vertical (up and down), horizontal (N-S), and horizontal (E-W). After obtaining the signal, it can then be analyzed using the HVSR method and obtain the dominant frequency and amplification values. This HVSR method compares the spectrum ratio of the horizontal component of the microtremor signal to its vertical component (Nakamura 1989).

The HVSR analysis method developed by Nakamura (1989) calculates the ratio of the Fourier spectrum of the horizontal component of the microtremor signal to its vertical component. The HVSR processing process, in general, can be seen in Fig 2. Mathematically Horizontal to vertical spectra ratio is expressed in equation 1 (Nakamura 1989).

$$R(f) = \frac{\sqrt{H_{EW}{}^2(f) + H_{NS}{}^2(f)}}{V_{UD}(f)} \quad (1)$$

Where *R(f)* is the spectrum of the HVSR ratio, $H_{EW}(f)$ is the spectrum of the horizontal component E-W, $H_{NS}(f)$ is the spectrum of the horizontal N-S component and $V_{UD}(f)$ is the spectrum of the vertical component.

The results of the HVSR analysis showed a spectrum peak at the dominant frequency. The dominant frequency (f_0) and the amplification factor (A) that describe the dynamic characteristics of the soil can be generated from the HVSR analysis (Nakamura 2000). Microtremor is mainly used to identify the soil's dominant frequency, the building's dominant frequency, and the resonance frequency of the building and soil structure beneath it (Moon et al. 2019).

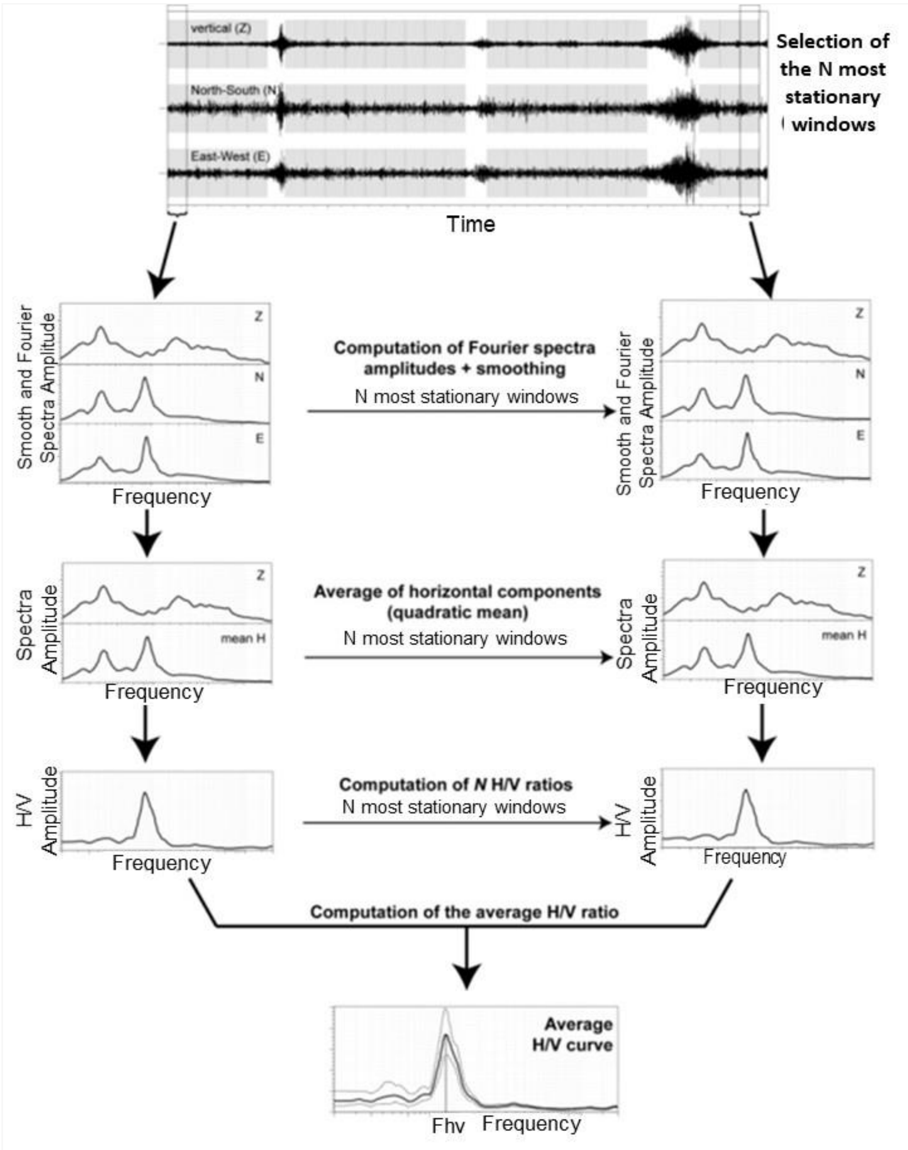

Fig 2. The flowchart shows the computation steps of the H/V ratio (Fergany and Omar 2017).

The floor spectra ratio (FSR) method is a method for determining the natural and resonant frequencies of buildings that describe the characteristics of buildings against earthquakes (Gosar et al. 2010). In the FSR method, other building characteristics that can be obtained besides the natural frequency are the building resonance index and the building vulnerability index. The natural frequency building value is determined from the spectrum analysis of each building floor to the ground below it. The data calculation process is carried out to determine the natural frequency value of the building using equations (2) and (3) (Prakosa et al. 2015).

$$f_0(FSR) = \frac{f_b NS}{f_t NS} \quad (2)$$

$$f_0(FSR) = \frac{f_b EW}{f_t EW} \quad (3)$$

Equations (2) and (3) are FSR analysis equations where f_b is the value of the building frequency, f_t is the value of the ground frequency, and NS-EW is the respective components of the data.

Resonance can be used to determine the level of possibility of a building experiencing resonance during an earthquake (Gosar et al. 2010). There are several classifications:

1. Low resonance (R>25%)
2. Medium resonance (15% <R< 25%)
3. High resonance (R<15%)

The building resonance index (R) is determined based on the spectrum of each component (NS and EW) which is calculated based on the following equation:

$$R = \left|\frac{f_b - f_t}{f_t}\right| \times 100\% \quad (4)$$

Where f_b is the natural frequency of the building, and f_t is the natural frequency of the ground.

The level of building damage is directly proportional to the soil vulnerability index (*Kg*). Soil vulnerability index is the vulnerability of the soil surface that results in deformation during earthquake waves. This vulnerability can be associated with lateral ground motion due to weak zones and fluid-filled rock pores.

Mathematically the formula for soil vulnerability index can be formulated in equation (5) (Nakamura 2000; Sungkono et al. 2011).

$$Kg = \frac{Am^2}{f_0} \quad (5)$$

where *Kg* is the soil susceptibility index, *Am* is the peak of the HVSR spectrum, and f_0 is the dominant frequency value. The value of the soil vulnerability index is classified to determine the level of vulnerability that can occur due to earthquakes (Table 1).

Table 1. Classification of soil vulnerability index values (Wulandari et al. 2018; Nakamura 1997).

Zone	*Kg* value
Low.	<3.
Medium	3-6
High.	.>6.

2.2. Building Vulnerability Index

The building vulnerability index can be estimated from the structure deformation associated with the seismic movement in the ground and the dynamic characteristics of the surface layers and structures. This is to estimate the possibility of damage to the building in an earthquake in the future, for example, to calculate the vulnerability index of buildings using equations (Mucciarelli et al. 2007; Sato et al. 2008; Akkaya 2020; Lantada et al. 2009; Sungkono et al. 2011):

$$K_{bi} = \frac{A}{4\pi^2 {f_0}^2 \cdot h_i} \quad (6)$$

Where *A* is the amplification factor of the FSR analysis on the soil and structure of the i-th floor. f_0 is the frequency value of the building's spectrum, and h_i is the height of the building on the i-th floor.

3. Methods

The research data used in this study are borehole accelerometer data located at a depth of 8 meters from the ground surface and accelerometer data located on the 1st, 2nd, and 3rd floors of the BMKG Building Region III Denpasar – Bali (Fig 3). The accelerometer used is the Raspberry Shake 4D Strong Motion Seismograph which measures three-wave components (east-west, north-south, and vertical components). Accelerograph data on boreholes were taken on July 31, 2020, and October 2, 2020, while accelerometer data on the 1st, 2nd, and 3rd floors were measured on September 24, 2020, from 03:00 to 13:00 eastern Indonesia time region (Fig 4).

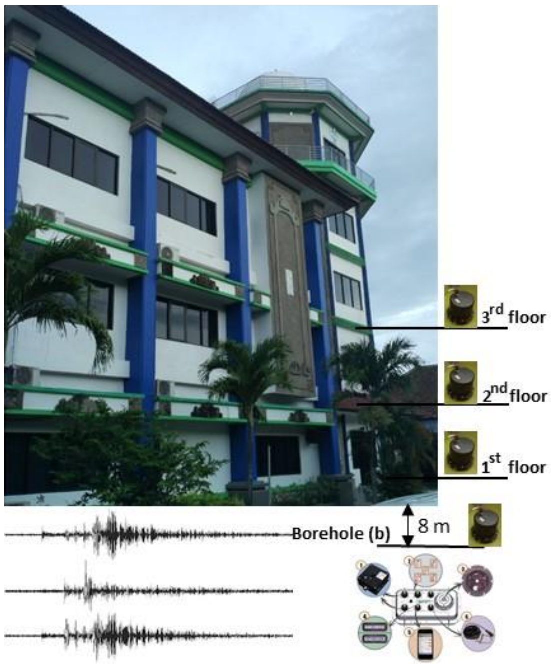

Fig 3. Location of the borehole accelerometer and building accelerometer.

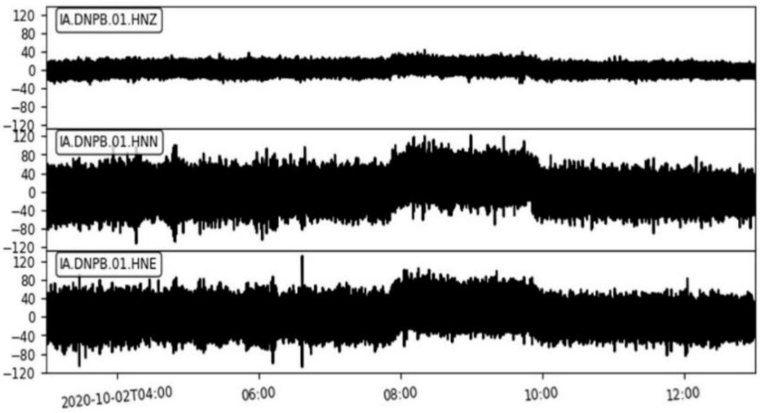

Fig 4. Accelerometer data were recorded at the borehole on October 2, 2020, from 03:00 to 13:00.

Processing of HVSR and FSR is carried out to obtain the value of the natural frequency of the soil, the natural frequency of the building, and the amplification factor. To find out the condition of the vulnerability of the building due to vibration, natural frequency analysis of the soil is carried out, natural frequency analysis of buildings, building resonance analysis, soil vulnerability index analysis, and building vulnerability index analysis is carried out.

4. Result discussions

4.1. Ground Natural Frequency

The results of processing soil microtremor data (boreholes) consisting of: natural frequency of the soil E – W direction (f_0s E-W), the amplitude of the soil E – W direction (A_0s E-W), the natural frequency of the soil N – S direction (f_0s N-S), the amplitude of the soil N – S direction (A_0s N-S), the natural frequency of the soil U-D direction (f_0s U-D), the amplitude of the soil U–D direction (A_0s U-D), horizontal to a vertical ratio (HVSR) on July 31, 2020, and October 2, 2020 data are shown at Table 2, Table 3, Fig 5, and Fig 6, respectively.

Table 2. The natural frequency of the soil value, horizontal to vertical spectrum ratio, and amplitude at July 31, 2020.

f_0s E-W (Hz)	**A_0s E-W**	**f_0s N-S (Hz)**	**A_0s N-S**	**f_0s U-D (Hz)**	**A_0s U-D**	**f_0s HVSR (Hz)**	**A_0s HVSR**
0.15	0.79	0.15	0.32	0.15	0.32	0.32	1.86

Table 3. The natural frequency of the soil value, horizontal to vertical spectrum ratio, and amplitude at October 2, 2020.

f_0s E-W (Hz)	**A_0s E-W**	**f_0s N-S (Hz)**	**A_0s N-S**	**f_0s U-D (Hz)**	**A_0s U-D**	**f_0s HVSR (Hz)**	**A_0s HVSR**
0.15	0.55	0.15	0.29	0.52	0.29	0.32	1.62

According to Kanai (1983), the value of the natural frequency of this soil is included in the soil classification type-I (f_0s) soil < 2.5 Hz) with a fairly thick sediment thickness, alluvial rock formed from delta sedimentation, topsoil, mud, and others with a depth of 30m or more. These results follow the study area's geological data, which consists of the Quaternary Alluvium Formation or the Holocene era, which has a lithology of gravel, gravel, sand, silt, and clay from the river, lake, and beach deposits (Hadiwidjojo et al. 1998).

Among the causes of variations in the shape of the HVSR curve are variations in impedance contrast, layer compactness, rock hardness, subsurface geology, and others. Herak (2008) mentions six parameters that affect the HVSR curve, namely primary wave velocity (Vp), shear wave velocity (Vs), layer thickness (h), layer density (ρ), quasi wave factor (Qp and Qs).

4.2. Building Natural Frequency

Microtremor data processing has been carried out on the 1st, 2nd, and 3rd floors measured on September 24, 2020, from 03:00 to 13:00 eastern Indonesia time region (Fig 7) to get the natural frequency value. The results of the calculation of the dominant frequency of the building (f0b) using the equation given by Nakamura (1989) get the value of the dominant frequency of the building (f0b) on the 1st floor = 1.28 Hz, the value of the dominant frequency of the building (f0b) on the 2nd floor = 0.5 Hz, and the dominant frequency value of the building (f0b) on the 3rd floor = 0.46 Hz (Fig 8). The calculation results show that the value of the building's dominant frequency (f0b) has the best value compared to the height of the building. The higher the building the value will have, the smaller the building's dominant frequency (f0b).

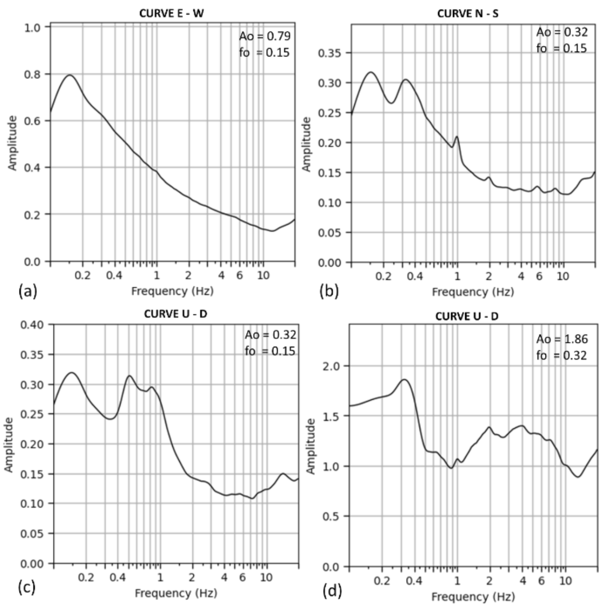

Fig 5. The results of processing the fast Fourier transform microtremor data to obtain the natural frequency value of the waves and the HVSR curve to obtain the natural frequency of the soil for the data on July 31, 2020. (a) The natural frequency

curve of the E-W component microtremor wave; (b) The natural frequency curve of the N-S component microtremor wave; (c) The natural frequency curve of the Z (U-D) component microtremor wave; (d) The HVSR curve of the soil (f_0 *HVSR*)

The value of the natural frequency of the building (f0b) BMKG Region III has a greater value than the value of the dominant ground frequency (f0t) so that the building is relatively safe from resonance.

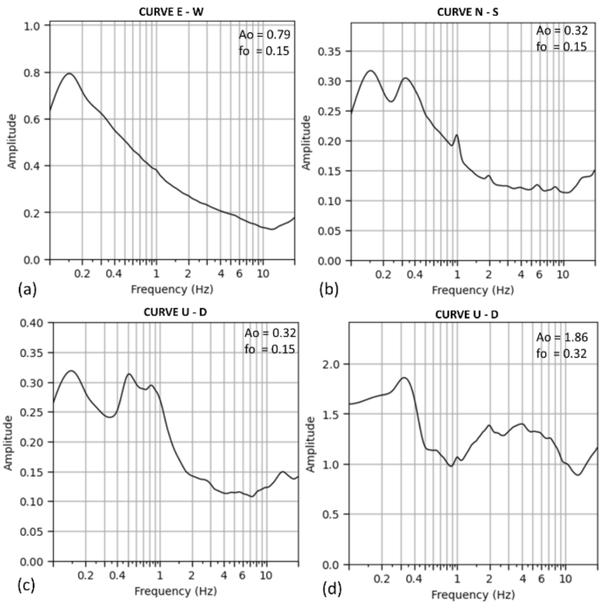

Fig 6. The results of processing the fast Fourier transform microtremor data to obtain the natural frequency value of the waves and the HVSR curve to obtain the natural frequency of the soil for the data on July 31, 2020. (a) The natural frequency curve of the E-W component microtremor wave; (b) The natural frequency curve of the N-S component microtremor wave; (c) The natural frequency curve of the Z (U-D) component microtremor wave; and (d) The HVSR curve of the soil (f_0 *HVSR*).

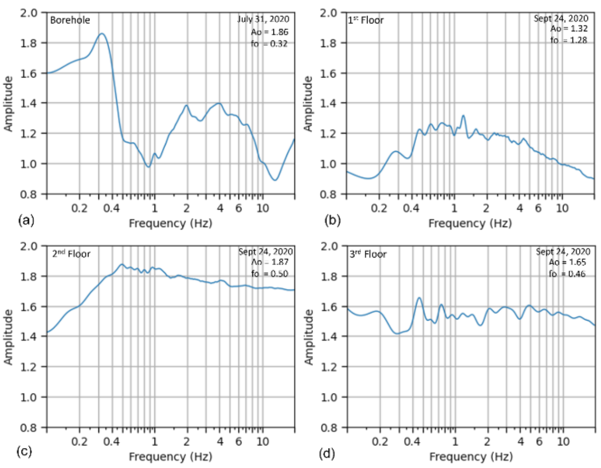

Fig 7. The horizontal to vertical spectral ratio curve of microtremor data processing results on the 1st, 2nd, and 3rd floors were measured on September 24, 2020, from 03:00 to 13:00 eastern Indonesia time region.

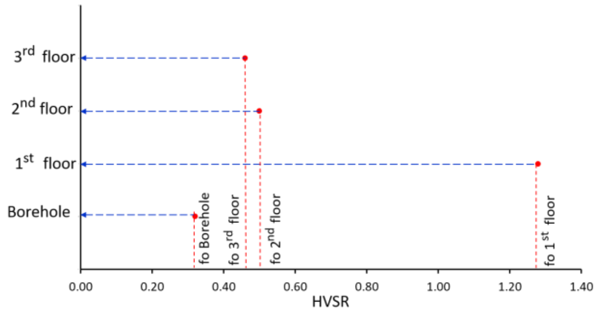

Fig 8. Graph of the relationship between the location of the microtremor measurement in the BMKG Region III Denpasar building with f_0 HVSR value.

4.3. Resonance Building and Ground (*R*)

The resonance value of the building with the ground has a value of 6.67% - 13.3%, with an average resonance value of 8.89%. Based on the classification made by Gosar et al. (2010), the resonance value obtained is included in the high resonance because the natural frequency of the building value is close to or equal to the value of the natural frequency of the soil. The resonance percentage value between the building and the ground is strongly influenced by the difference in value between the soil's natural frequency and the natural frequency of the building above it. For example, suppose the natural frequency of the building is closer to the natural frequency of the soil. In that case, the resonance percentage value is getting smaller, which means that the building vulnerability level to the soil is getting higher, and the resonance possibility between the soil and the building is also getting more significant. On the other hand, if the natural frequency value of the land and the buildings has a more significant difference, then the value of the resonance percentage is more significant, meaning that the level of vulnerability of the building to the soil is low. The possibility of resonance between the soil and the building is also getting smaller.

4.4. Soil Vulnerability Index

The results of processing soil vulnerability using the equation that Nakamura (2000) and Sungkono et al. (2011) get a soil vulnerability value of 10.81 for the measurement results on July 31, 2020, and 8.20 for the measurement on October 2, 2020. The results of the soil vulnerability index are following the results research conducted by previous researchers found that the research area was included in the category of low to moderate vulnerability index, namely 0.95 <Kg>18.76 (Murdiantoro et al. 2016; Kurniawan et al. 2017; Pratama et al. 2020). According to Daryono et al. (2009), Kg <10 has a low soil vulnerability index, 10<Kg<20 is in the medium category, and Kg>20 is classified in the hazard zone.

4.5. Building Vulnerability Index

The building vulnerability index (Kb) shows the level of damage that occurs to the building in the event of an earthquake. The greater the vulnerability value of a building, the greater the potential damage that will occur (Sato et al. 2008). The data processing results get the vulnerability index value (Kb) of the BMKG building between 0.4827 to 7.9771. The 1st floor has the high vulnerability index, and the 3rd floor has the lowest vulnerability index (Table 4).

Table 4. Building Vulnerability Index Table.

Location	Building Vulnerability Index (*Kb* E-W)	Building Vulnerability Index (*Kb* N-S)
1st Floor	0.931015	7.977052
2nd Floor	0.590797	5.213707
3rd Floor	0.482705	0.812579

5. Conclusions

The results of processing and analyzing the characteristics of microtremor data in the BMKG Region III Denpasar Bali building get:

- The natural frequency value of soil (f_0s) 0.28 Hz - 0.29 Hz, which is included in the soil classification type I (f_0s) soil < 2.5 Hz) with a fairly thick sediment thickness, alluvial rock formed from delta sedimentation, topsoil, and mud. with a depth of 30 m or more. These are consistent with the geology, which consists of the Quaternary alluvium Formation, which has a lithology of gravel-to-gravel sand, silt, and clay from the river, lake, and beach deposits.
- The dominant frequency value of the building (f_0b) on each building is 1.28 Hz on the 1st floor, 0.5 Hz on the 2nd floor, and 0.46 Hz on the 3rd floor. The natural frequency of the building (f_0b) value has a greater value than the dominant ground frequency (f_0t) so that the building is relatively safe from resonance.
- The building's resonance value (*R*) with the ground is 6.67% - 13.3%, with an average resonance value of 8.89%, and that value is the high resonance category; because the natural frequency value of the building is not close or equal to the natural frequency value of the soil.
- The building is located in an area with a soil vulnerability (*Kg*) value of 8.20 – 10.81, which is included in the low to moderate soil vulnerability index. Meanwhile, the building vulnerability index (*Kb*) found that the building has a value of 0.4827 – 7.9770, with the 1st floor having the highest vulnerability index. The value of the building vulnerability index shows that it is in a low category (safe).

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