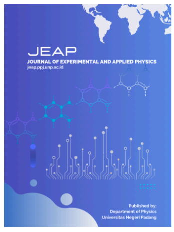
Journal of Experimental and Applied Physics
Journal Homepage: jeap.ppj.unp.ac.id
Vol. 4, No. 1, March 2026.
ISSN (Print): 2988-0378 ISSN (Online): 2987-9256



Analysis of Seismic Vulnerability Index Based on Microtremor Signal Measurements in Balingka Agam Regency

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Article History
Received : August, 03rd 2025
Revised : March, 12th 2026
Accepted : March, 12th 2026
Published : March, 31st 2026

DOI:
https://doi.org/10.24036/jeap.v4i1.120

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Abstract: This study aims to analyze the seismic vulnerability index ($\boldsymbol{K_g}$) in Nagari Balingka, Agam Regency, West Sumatra, which is located near the Sianok Segment. The Sianok segment is part of the active Sumatra Fault, making Balingka prone to seismic activity, especially earthquakes caused by fault segment movement. The method used is the Horizontal to Vertical Spectral Ratio (HVSR) based on microtremor signals. Microtremor signal recording was conducted at 16 measurement points scattered throughout Balingka. Microtremor signal recording data analyzed using the HVSR method will produce an H/V curve. The curve represents the dominant frequency value ($\boldsymbol{f_0}$) and amplification factor ($\boldsymbol{A_0}$) correlated with the seismic vulnerability index ($\boldsymbol{K_g}$). The results of the microtremor analysis were used to create a map of the distribution of $\boldsymbol{f_0}$, $\boldsymbol{A_0}$, and $\boldsymbol{K_g}$ using QGIS software. The results of the study indicate that the dominant frequency values range from 1.9 to 14.75 Hz. Meanwhile, the amplification factor ($\boldsymbol{A_0}$) ranges from 1.7 to 5.79. Based on the dominant frequency ($\boldsymbol{f_0}$) and amplification factor ($\boldsymbol{A_0}$), the seismic vulnerability index ($\boldsymbol{K_g}$) in Nagari Balingka ranges from 0.46 to 8.71.

Keywords: amplification factor, dominant frequency, HVSR, Nagari Balingka, seismic vulnerability index

1. Introduction

Earthquakes are tremors occurring on the Earth's surface, triggered by the release of internal energy, which is primarily driven by the shifting of tectonic plates. This plate movement causes energy to build up, serving as the main catalyst for seismic events. Once released, this energy propagates outward as seismic waves, ultimately resulting in ground shaking or tremors felt at the surface[1]. West Sumatra is an area with a high risk of earthquakes because it is located at the meeting point of two colliding tectonic plates. The province is located on the Semangko fault line, the Mentawai fault line, and the subduction zone. There are four segments of the Semangko Fault in West Sumatra: the Sianok segment in Agam Regency, the Sumpur segment in Tanah Datar, the Sumani segment in Solok, and the Suliti segment in South Solok [2]. One of the four segments that is still active is the Sianok Segment. According to the National Earthquake Study Center in 2007, the Sianok segment has an estimated length of approximately 90 kilometers and an estimated

How to cite:
S. S. Ramadhan, H. Amir, Zulhendra, F. U. Jhora, 2026, Analysis of Seismic Vulnerability Index Based on Microtremor Signal Measurements in Balingka Agam Regency, *Journal of Experimental and Applied Physics,* Vol.4, No.1, page 15-24.
https://doi.org/10.24036/jeap.v4i1.120

maximum magnitude (Mmax 7.4). Agam Regency, Bukittinggi City, and Padang Panjang City are the three areas that cross the Sianok segment [3].

In 1822, the Sianok segment experienced a strong earthquake that was recorded in its seismic history, with a magnitude of approximately Ms ~ 7. The area around the Sianok segment experienced its last major earthquake on March 6, 2007, noted at around Mw 6.4. In this earthquake, 67 people lost their lives, 826 were injured, and 34,719 homes were damaged as a result of the earthquake. Given the recurring seismic activity, the fault zone after a major tremor that occurred in 2007, is anticipated to accumulate tectonic stress continuously, thereby increasing the potential for a future powerful seismic event. [4]. In addition to these tectonic factors, the level of damage caused by earthquakes is also greatly influenced by local geological conditions and soil characteristics in the area. Variations in rock types and surface deposits can affect the amplification of seismic waves reaching the ground surface. Therefore, understanding the geological conditions around the Sianok segment is important for assessing the potential response of the ground to earthquake shocks.

According to Geological Map of Padang (Kastowo et al., 1996) and the Solok Geological Map (Silitonga et al., 2007), the Sianok Segment generally passes through Quaternary volcanic deposits and surface deposits such as alluvium and terrace deposits. Volcanic deposits from the Quaternary period are derived from volcanic activity in the northern region of Lake Singkarak, notably from volcanoes like Tandikat, Singgalang, and Marapi.. In the step-over zone, there are Permian to Triassic-aged rocks (metamorphic rocks) consisting of the Filit and Serpih Members of the Kuantan Formation, the Batu Tulis Member of the Tuhur Formation, and limestone intrusions (granite) [5]. This lithological diversity indicates that the area around the Sianok segment has complex geological conditions that can affect the soil's response to seismic waves. Differences in rock types and surface deposits can cause variations in the level of earthquake vibration amplification at each location. Therefore, the areas around the Sianok segment need to be further studied to determine the local geological characteristics and potential vulnerability to earthquake shocks.

Balingka is a village located in IV Koto Subdistrict, Agam Regency, West Sumatra. This village is located close to the Sianok segment, which has the potential for seismic activity, especially earthquakes caused by fault segment movement. In addition to geological aspects, Balingka is part of the route connecting the Sicincin-Malalak-Balingka area [6]. This route is frequently used by the community as an alternative route to Bukittinggi City, especially when the main route experiences congestion or disruptions, making the sustainability of infrastructure and the safety of people traveling along this route a matter of great importance. The geological characteristics of Nagari Balingka influence how the ground behaves during an earthquake. To understand the potential damage caused by seismic shaking, it is essential to understand the geological conditions. Seismic vulnerability analysis is a crucial component of disaster mitigation planning in this region.

The vulnerability of soil to deformation during earthquakes can be identified through seismic vulnerability index values. The seismic vulnerability index is a measure associated with how vulnerable an area is to the threat of earthquakes. An area with a high seismic vulnerability index typically faces an elevated risk of earthquake-related hazards. [7]. The seismic vulnerability index can indicate the level of shaking that occurs in an area due to an earthquake. Damage caused by local effects during an earthquake is characterized by low dominant frequencies with significant amplification [8]. A seismic vulnerability index is derived through analysis based on microtremor signal data using the Horizontal to Vertical Spectral Ratio (HVSR) method [1].

Microtremor is a passive seismic measurement by capturing vibrations or ambient waves generated by both natural conditions and anthropogenic activities near the seismometer location. Microtremor has wave characteristics that propagate across the surface; hence, it is also referred to as noise. Microtremor is used to assess subsurface structural conditions by analyzing dominant frequencies and amplification factors [9]. The displacement amplitude of microtremors ranges from 0.1 to 1 micron, and the velocity amplitude ranges from 0.001 to 0.01 cm/s, which are detected by high-sensitivity seismographs. Microtremors are divided into two types based on duration. Short-period microtremors have a duration of less than 1 second and are associated with shallow subsurface structures several tens of meters wide. Long-period microtremors have a duration of more than 1 second and are associated with deeper soil structures with wind speeds of 3 km/second [10]. Microtremor data can be applied in earthquake-resistant building design by identifying the natural frequencies of the soil in a given area, thereby avoiding potential resonance. Additionally, microtremor measurements are employed to classify soils by their degree of hardness [11].

The most commonly used method for analyzing microtremors is the HVSR (Horizontal to Vertical Spectral Ratio) method. The Horizontal to Vertical Spectral Ratio (HVSR) method is an approach that compares the vibration spectrum in the horizontal direction with the vibration spectrum in the vertical direction of the microtremor signals. This analysis aims to identify subsurface characteristics, particularly in determining the physical conditions and dynamics of soil layers in a region. This method is used to estimate the dominant frequency and local amplification from microtremor data [12]. The HVSR method utilizes the natural harmonic vibrations of the soil caused by natural activities [13]. The HVSR method is one of the most effective initial methods for mapping the vulnerability of soil in a particular area. By applying this method, a map of soil vulnerability distribution in the study area can be generated, which serves as a reference and basis for consideration in development planning [5]. The HVSR method processing process is carried out through the following stages. a. Vibrations from the ground surface are recorded using micro-seismic sensors. b. Data in the form of time series is collected from each vibration component; at this stage, ambient signals (natural vibrations) are then cut for further processing. c. Fourier transformation is applied to the data from the vertical and horizontal components (north–south, east–west), resulting in Fourier spectrum. d. The HVSR curve, as well as the dominant frequency (f_0) and peak amplitude (A_0) values, are obtained by dividing the average spectrum of the horizontal component by the vertical spectrum.

Research on seismic vulnerability indices using microtremors with the HVSR method has been conducted in various areas, such as Kulonprogo. The results of the study indicate that the dominant frequency (f_0) within the research area varies between 1.1 - 18.4 Hz, the amplification factor ranges from 1.4 - 6.2, and the highest seismic vulnerability index value of 22.4 is located in the Jatirejo area, Lendah District. In the event of an earthquake in Yogyakarta and its surroundings, the Jatirejo area is likely to be more vulnerable to damage than other areas, potentially suffering more severe damage due to the earthquake [14]. Then, research was conducted in Bukit Nobita, Padang City. The results of the study showed that the hilly areas and settlements were not at risk from seismic activity and remained secure during seismic events because the seismic vulnerability index values in both study areas fell into the low category of less than 3 [15].

2. Materials and Method

2.1 Data Collection

Microtremor signal measurements were conducted at 16 measurement locations spread across Balingka. Microtremor signal recording was conducted with a recording duration of 25–30 minutes, referring to SESAME European Research [16]. The distance between one measurement point and another was 250–500 m. The instrument used to record ground vibrations was a Type S3S seismometer. The microtremor signals generated from the measurements consisted of three components: two horizontal components (east-west and north-south) and one vertical component.

Figure 1. Research location in Nagari Balingka

2.2 Data processing

Microtremor data processing refers to the SESAME Europan Research standard [16]. Microtremor signals obtained from measurements are processed using Easy HVSR software. This processing aims to eliminate noise in the microtremor data. The microtremor recording results are in the form of signal data in sg2 format. The data is then analyzed using the HVSR method by comparing the vertical and horizontal signal components using equation (1).

$$HVSR = \sqrt{\frac{[(S_{North-South})^2 + (S_{East-West})^2]}{S_v}} \tag{1}$$

In Easy HVSR, microtremor data is input into read traces to read three components, namely the vertical component, North-South, and East-West. After the raw microtremor data is input into the Easy HVSR software, the next step is window selection, which determines the window size used to divide each component wave into time windows. At this stage, the time window size is divided into 20 seconds. This is useful when removing noise, because when removing windows that are considered noise, the time cut is 20 seconds per window and the initial time starts at 0 seconds. The next step is to remove noise using manual selection. Noise is a sudden wave. The next step is spectral analysis, which serves to determine the minimum and maximum frequency ranges, useful for determining the frequency values that appear at the peak of the curve. The values used are 0.1–10 Hz. Next is the smoothing stage, using the Konno-Omachi smoothing type with a percentage of 5-10% and a bandwith of 40. This smoothing stage can affect the clarity of the $f0$ peak.

3. Results and Discussion

3.1. Dominant Frequency (f_0)

The characteristics of soil in a location can be identified through dominant frequency values. The value of the dominant frequency is related to the depth of the reflection plane of a wave beneath the surface of the study area. This reflection plane is generally the boundary between sedimentary layers and hard rock [9]. In HVSR analysis, the frequency that naturally occurs in the region is known as the dominant frequency. When an area experiences an earthquake or vibration occurs with a frequency identical to the dominant frequency, seismic waves in the area will be amplified due to resonance [11]. Dominant frequency value indicates the geological characteristics of the research location according to its response to earthquakes.

Region with high dominant frequency tend to have hard rock characteristics and thin sediment layers. Conversely, region with small dominant frequency are prone to earthquake disasters because they have soft rock characteristics and high sediment thickness [17]. Rock characteristics that indicate soil classification based on dominant frequency values in Balingka can be seen in Table 1.

Table 1. Classification of soil according to dominant frequency value in Balingka

Measurement poin	**Soil Classification**	**Dominant Frequency (Hz)**	**Description**
T9, T11, T14	Type IV	6,7-14,75	Tertiary rocks consisting of hard gravelly sandstone
T3, T5, T7, T10, T12	Type III	4,0-6,4	Alluvial rocks consisting of sandy gravel, sandy hard clay, and loam
T1, T2, T4, T8, T15, T16	Type II	2,5-4,0	Alluvial rock consisting of sandy hard clay, sandy gravel
T6, T13	Type I	1,9-2,2	Alluvial rock formed from delta sedimentation, topsoil, mud, soft soil, humus, delta deposits, or mud deposits, which are classified as soft soil.

The recorded dominant frequency measurements in the research area varied between 1.9-14.75 Hz. The distribution of dominant frequency values (f_0) can be seen in Figure 2. Measurement points T9, T11, and T14 were categorized as type I with f_0 values ranging from 6.7 Hz to 14.75 Hz, indicated by a red color degradation. This indicates that seismic waves do not undergo significant attenuation and directly impact the bedrock. This characteristic causes earthquake waves passing through this area to not undergo amplification, making them more stable against earthquake shaking and having a low vulnerability to building and infrastructure damage.

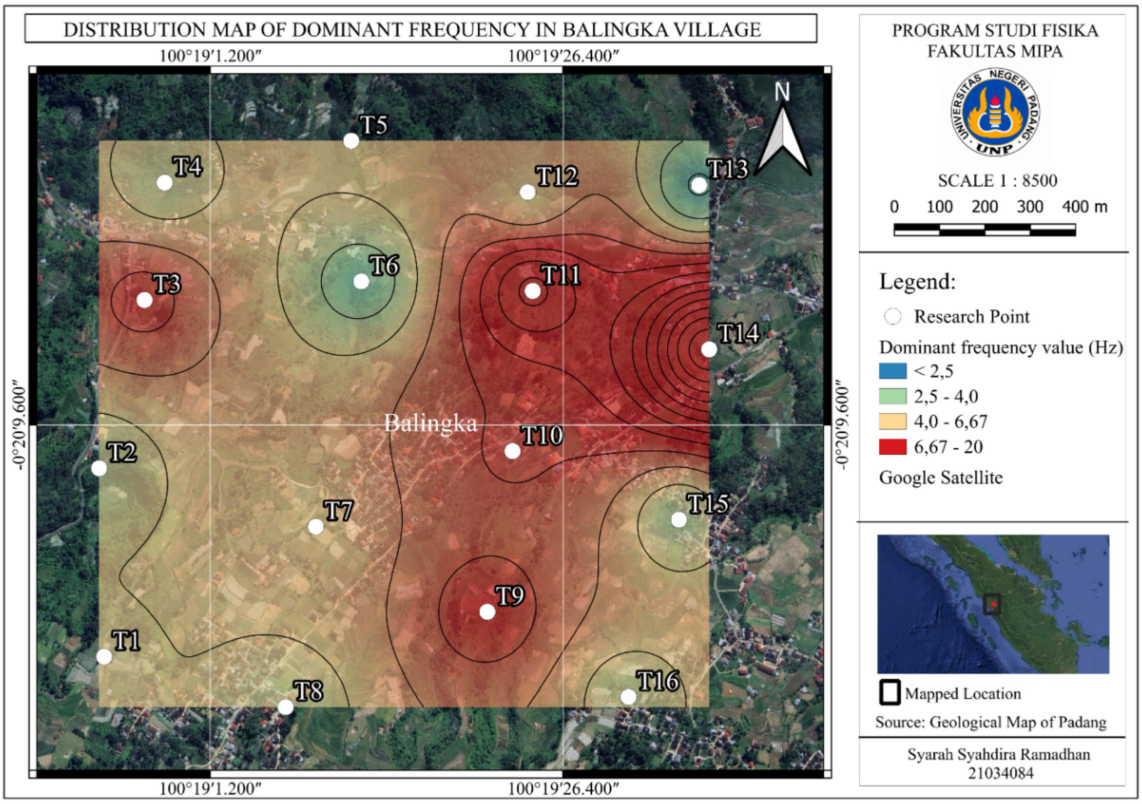

Figure 2. Distribution Map of Dominant Frequency in Nagari Balingka

The measurement locations at T3, T5, T7, T10, and T12 are classified as Type II soil with a f_0 value between 4 Hz and 6.4 Hz, consisting of sandy gravel, alluvial rock, loam and sandy hard clay. Type III soil is present at measurement points T1, T2, T4, T6, T8, T15, and T16, with a lower dominant frequency range of 2.5–4 Hz. This frequency range indicates the presence of thick sediment layers, suggesting that seismic waves passing through this area are at risk of amplification, resulting in moderate potential damage from earthquake shaking. The soil types in this category are sandy clay and sandy gravel.

The research location has a low dominant frequency value of around 1.9-2.2 Hz and is classified as type IV. This characteristic indicates that the measurement location is on a thick sediment layer with relatively soft material. This condition causes waves passing through this area to undergo greater amplification because the waves are trapped and resonate within the sediment layer. The soil types in this category include topsoil, mud, soft soil, humus, delta deposits, or mud deposits, which are classified as soft soils with high porosity and low density.

3.2. *Amplification* (A_0)

Amplification is the enlargement of seismic waves that occurs due to significant differences between layers. The amplification factor is controlled by the impedance contrast between soft layers (sediment) and bedrock Seismic waves that propagate through soft soil layers will experience greater energy amplification than when propagating through harder rock layers. This causes earthquake tremors to feel stronger in areas with soft soil characteristics. Thus, soft soil will cause greater earthquake intensity than hard rock at the same distance and earthquake source [18]. The magnitude of amplification depends on the impedance difference between sediment layers and bedrock. Additionally, local geological conditions such as topography and ground motion resonance contribute to increased damage caused by earthquakes [19]. Table 2 shows the classification of amplification.

Table 2. Classification of amplification factor values in Balingka

Measurement point	Amplification Factor Value	Zone	Classification
T2, T3, T5, T6, T7, T8, T10, T13, T14, T15, T16	1,7 - 2,8	1	Low
T1, T4, T9, T11, T12	3,01 – 5,79	2	Medium

Based on measurements in the study area, the amplification factor values in Balingka ranged from 1,7 to 5,79. According to Table 2, these amplification values fall within the low and moderate zones. Areas in the low zone are indicated by green, while those in the moderate zone are indicated by yellow. The lowest amplification value is at measurement point T8, and the highest value is at T1. This range of values indicates differences in subsurface characteristics at each measurement location, which influence the soil's ability to amplify seismic waves during an earthquake. These differences play a crucial role in determining the extent of seismic wave amplification at each measurement point during an earthquake.

With reference to the classification of amplification factor values in Table 2, it was found that the study area with $A_0 < 3$ or low category was located at measurement points T2, T3, T5, T6, T7, T8, T10, T13, T14, T15, and T16. Low amplification values indicate that there is little difference between subsurface layers (impedance contrast) in the study area. Areas with moderate amplification values are located at measurement points T1, T4, T9, T11, and T12, which have values ranging from 3,01 to 5,79.

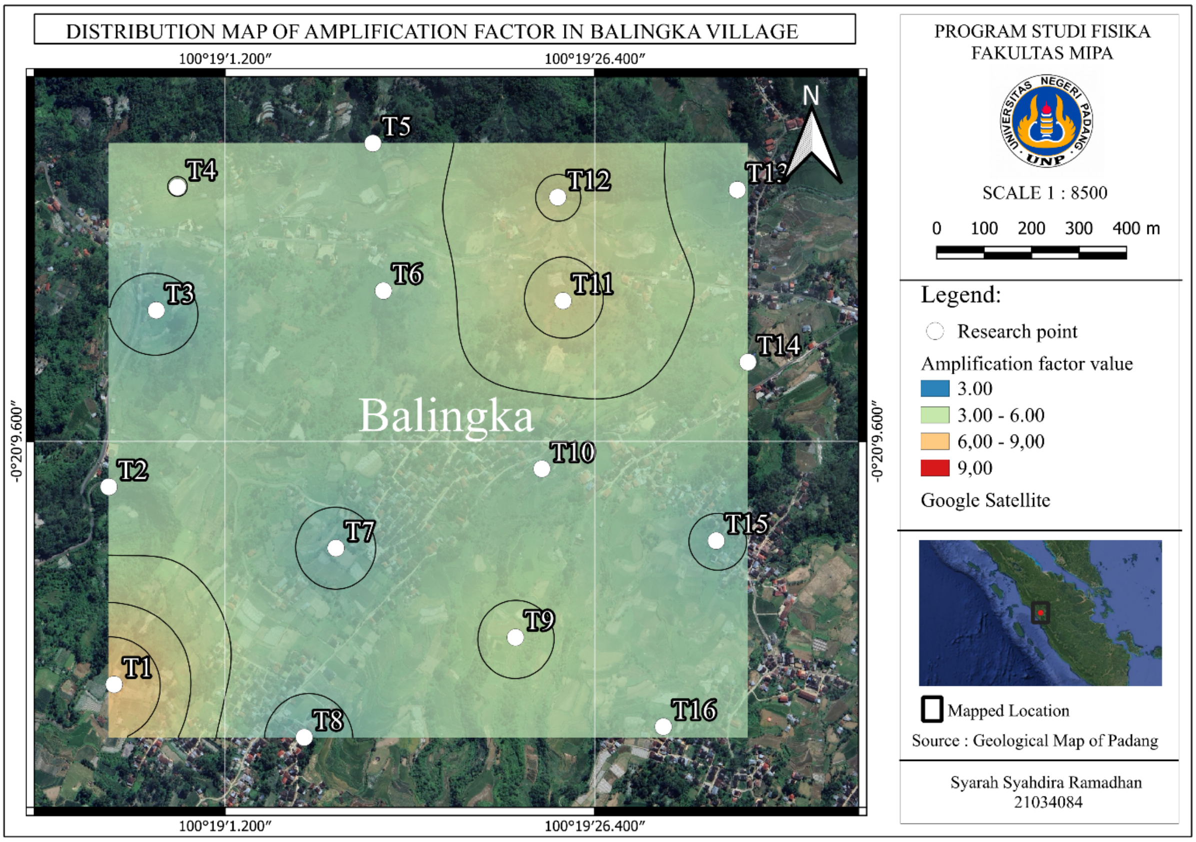

Figure 3. Distribution Map of Amplification Factor in Nagari Balingka

The difference in amplification values obtained is caused by the degree of deformation (weathering, folding, and faulting). The amplification factor value will increase if the soil or rock layer undergoes deformation that changes the properties of the rock. Amplification values can vary in the same rock depending on the level of deformation in the weathering process that occurs in the rock. This indicates that in the same rock, geological conditions in one area may differ from those in another area due to deformation processes that alter the geological characteristics of a particular region.

3.3. Seismic Vulnerability Index (K_g)

One of the microseismic measurement parameters in earthquake microzonation is the seismic vulnerability index, which indicates the degree of vulnerability of the surface soil layer to soil deformation that occurs during an earthquake [13]. Table 3 shows the classification of K_g values.

Table 3. Classification of seismic vulnerability index values in Balingka

Measurement point	Seismic Vulnerability Index Value	Zone	Classification
T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T14, T15, T16	0,46 – 2,68	1	Low
T12, T13	3,03 - 4,2	2	Medium
T1	8,71	3	High

The seismic vulnerability index (K_g) can be obtained using the following equation:

$$K_g = \frac{{A_0}^2}{f_0} \quad (4)$$

Amplitude (A_0) and dominant frequency (f_0) have a significant influence on the seismic vulnerability index value. When the maximum amplitude value and dominant frequency are small, the seismic vulnerability index value will be greater. Conversely, if the minimum A_0 and f_0 are high, the K_g will be smaller [13]. High K_g are typically identified on soil with soft sedimentary rock lithological characteristics. This indicates that the region is at risk of seismic hazards. Conversely, low $K_g$values are typically found in soils with a solid rock composition and high stability, so during an earthquake the vibrations felt in these areas are relatively weak [20].

Based on the results of data processing as shown in Figure 4, the seismic vulnerability index values in Nagari Balingka range from 0,46 to 8,71. Areas classified as low range from 0,46 to 2,68, located at measurement points T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T14, T15, and T16. The low K_g values indicate that the soil structure stability in these areas is high. Areas with moderate vulnerability index values ranging from 3,03 to 4,2 are located at measurement points T12 and T13. These values indicate that this region has a significant potential for earthquake wave amplification. This condition suggests the presence of thick sediment layers that amplify seismic waves, resulting in relatively high amplification values. Thick sediments cause waves to be trapped longer, resulting in this area having the potential to experience stronger shocks during an earthquake.

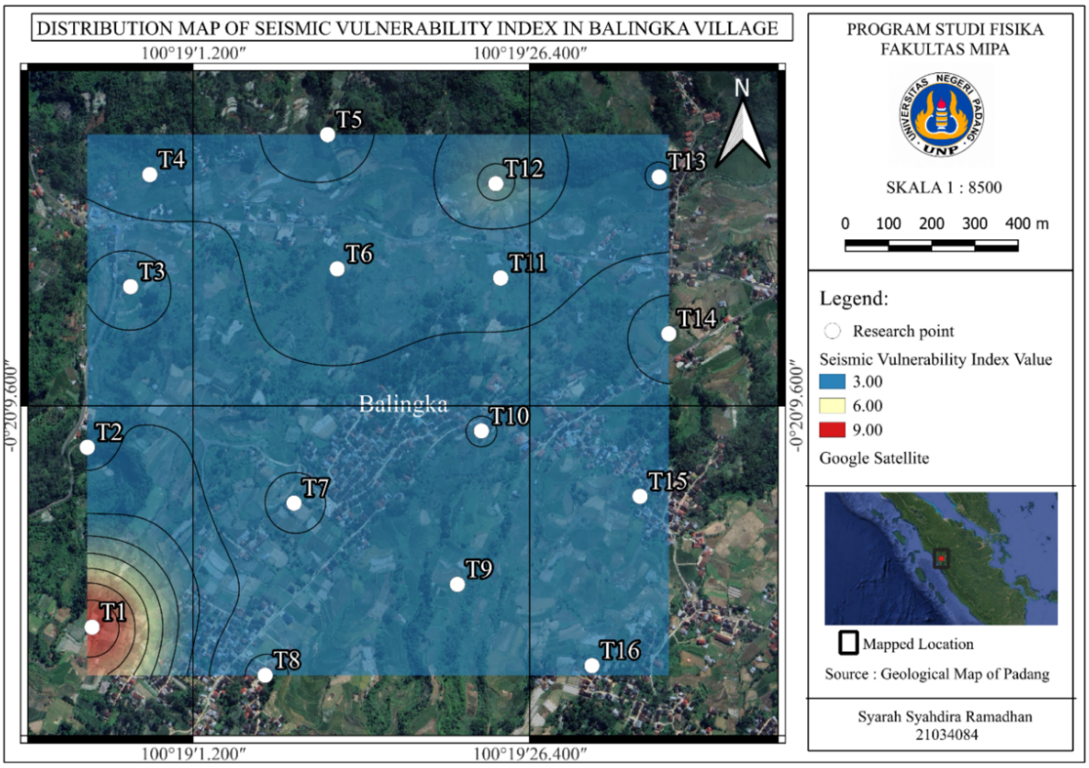

Figure 4. Distribution Map of Seismic Vulnerability Index in Nagari Balingka

A high vulnerability index value of 8,71 was recorded at measurement point T1. The high seismic vulnerability index value is due to the fact that this region has a large amplitude and a dominant frequency in the low range. This area shows a high potential for seismic wave amplification. These high values indicate that the subsurface in the measurement area is dominated by very thick and soft sediment layers with high impedance contrast values. The high seismic vulnerability index value is classified as a high-risk zone for building or infrastructure damage in the region.

4. Conclusion

The data processing results from 16 measurement points in Nagari Balingka show that low seismic vulnerability index (K_g) values dominate the measurement area. This means that Nagari Balingka is in a zone with low risk of seismic shocks. Amplification factor values (A_0) range from low to medium. The dominant frequency values (f_0) vary in range, where low f_0 values indicate the presence of thick sediment layers, while high f0 values indicate the presence of hard rock with thin sediment layers. In areas with low to moderate earthquake vulnerability indices, infrastructure development must comply with earthquake-resistant building standards and integrate structural designs that accommodate potential seismic activity.

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