SEISMIC VULNERABILITY MICROZONATION USING HORIZONTAL TO VERTICAL SPECTRAL RATIO (HVSR) METHOD IN GARUNGLOR VILLAGE AND ITS SURROUNDINGS WONOSOBO REGENCY

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ABSTRACT

This research makes a significant contribution to geotechnics and seismology by providing a database of dominant frequencies and amplifications in Indonesia. The results can be used for spatial planning, earthquake risk mitigation, and understanding variations in soil characteristics and potential seismic amplification across regions to support safer development. Garunglor Village and its surroundings in Sukoharjo District, Wonosobo Regency, have a thick sedimentary layer dominated by alluvial rocks, topsoil, and mud, with low dominant frequencies. At several rock formation measurement points (Tomt, QTlb, and Tptl), the dominant frequency values varied, indicating diverse sediment characteristics. Low seismic wave amplification was found at 5 research points. The seismic vulnerability index was also low at the 8 research points, with T12 having the lowest value, making it the most suitable area for relocation. These results indicate that areas with low amplification and vulnerability indexes in Garunglor Village and its surroundings are relatively safe from potential earthquakes.

Keywords: Dominant Frequency; Susceptibility Index; Geopysics; HVSR; Amplification; microseismic

Introduction

Natural disasters are natural events that cause harm to humans. These events result in loss of life, environmental damage, property loss, and psychological impact. Natural disasters cannot be predicted with great accuracy, but the impact of disasters can be anticipated so that the losses incurred can be minimized. One of the natural disasters that often occur in Indonesia and cannot be predicted in detail is landslides and earthquakes. Landslides are a serious threat to the security and welfare of the people in Indonesia. The country, with its diverse topography and extreme weather, experiences frequent landslide events that can have detrimental impacts.[1] According to Subakti,[2] vulnerability to earthquakes and landslides is influenced by a number of factors, including geology, land use, and climate change.

The existence of geological structures has triggered various problems of land instability, road damage, and has become one of the factors that trigger landslides.[3] To understand the potential for landslides in an area, a geomorphological approach is used.[4] Indonesia's geographical location on the Pacific Ring of Fire places it in a vulnerable position to tectonic and volcanic activities, creating geological conditions that favor landslides.[5] Uncontrolled land use factors, including deforestation and unsustainable human activities, also exacerbate the level of vulnerability to landslides.[6] Climate change, such as increased extreme rainfall and

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changing seasonal patterns, has the potential to increase the frequency and intensity of landslides.[7] Historical data shows that some areas, such as Java, Sumatra and other regions, have consistently experienced significant landslide events.[8] The impacts of landslide events are not only physically and economically detrimental, but also threaten the safety of the population, causing fatalities, loss of shelter, and damage to critical infrastructure.[9]

The Central Java region of Indonesia has a high earthquake potential as it is located in a seismically active zone caused by the meeting of the Indo-Australian and Eurasian tectonic plates.[10,7] In addition, there are several active faults in this area, such as the Opak Fault and the Semarang Fault, which can trigger earthquakes of significant magnitude. According to Ramdhan[11] the presence of active volcanoes, such as Mount Merapi, also increases the risk of volcanic earthquakes. These factors make Central Java vulnerable to earthquakes that could have a major impact on infrastructure, population and economic activity in the region.

Based on earthquake data recorded on BMKG Banjarnegara's official social media, the Wonosobo area recorded 29 earthquakes from January to September 2023. In early 2023 Wonosobo experienced quite frequent earthquakes in a week. The impact of the Wonosobo earthquake was also felt, especially in Garunglor village, Sukoharjo sub-district. The impact that occurred at that time was a very pronounced shock; several houses with sturdy structures cracked. so that residents are worried because the area where they live is prone to earthquakes and landslides. The following is a picture of one of the buildings in Garunglor village that was affected by the II-III MMI earthquake, which continued to occur.

An earthquake is an earth tremor event that occurs due to a sudden release of energy in the Earth, which is usually characterized by the fracture of rock layers in the Earth's crust. The energy that causes earthquakes is generated by the movement of tectonic plates. The BMKG website in 2017 explains that the energy released spreads in all directions in the form of seismic waves, so that the vibrations can be felt on the earth's surface. The thickness of the sedimentary layer is one of the factors that affect the local site effect. Local site effect is the language of the influence of the local geological conditions of the surrounding area on the ground vibrations that occur due to earthquakes. The thickness of the sedimentary layer can be seen by the vibration of the dominant frequency of the rock.[4] The dominant frequency value is closely related to the depth of the subsurface wave reflection plane. The reflection plane is the boundary between loose sediments and hard rock. The lower the frequency generated from the reflected waves, the thicker the sediment and the deeper the reflected plane.[8] Areas with low dominant frequency ($f0$) values indicate that they are susceptible to long-period vibrations, which could potentially endanger tall buildings.[2] This is because tall buildings have low dominant frequencies, which can cause resonance if built in areas with low dominant frequencies.

Figure 1. Head of Hamlet 1 Hall of Garunglor Village

The thickness of the sedimentary layer also affects the amplification in the area.[12] Farazi[13] says that the value of the soil amplification factor is related to the ratio of the impedance contrast of the surface layer to the underlying layer. According to Pischiutta,[14] the increase in seismic waves that occurs due to significant differences between soil layers is referred to as amplification. In other words, seismic waves will increase if they travel from one medium to another that is softer than the initial medium. The greater the difference between the mediums, the greater the wave enhancement. Amplification has a physical meaning as the maximum amplitude that can be observed from the frequency values that often appear, so that it can represent the characteristics of rock layers in an area.[15] Amplification is related to the impedance contrast between the surface and underlying layers, leading to variations in amplification across different regions. This impedance contrast is influenced by the densities and wave velocities of the surface and underlying layers. The greater the impedance contrast between the two layers, the higher the amplification factor. High amplification values can cause damage to nearby buildings.[16] Therefore, information on the thickness of the sedimentary layer in an area has an important role in earthquake disaster mitigation.

The dominant frequency and amplification values can provide information on the thickness of soft soil layers, soil stiffness, and potential seismic vibration amplification that may occur during an earthquake.[17] Nakamura[18] proposed the HVSR method to estimate the natural frequency and amplification of local geology from microseismic data. The important parameters resulting from the HVSR method are natural frequency and amplification. HVSR measured on the ground aiming to characterize the local geology, the natural frequency and amplification are related to the subsurface physical parameters.[19] The Horizontal to Vertical Spectral Ratio (HVSR) method has developed into one of the effective methods for soil characterization.[20] The dominant frequency is the most frequently occurring frequency and is considered to be the representative frequency of the rock layers in an area, which can also indicate the type and characteristics of the rock.[21] The dominant frequency value obtained from the calculation using the HVSR method reflects the natural frequency of the area, meaning that if an earthquake or vibration occurs with the same frequency as this natural frequency, it causes resonance amplification of seismic waves in the area. The frequency of microtremors according to research from[22] and[23] ranges from 0.5 to 20 Hz, but for microtremors with low frequencies it can reach 0.2 Hz. The HVSR method uses microvibration (microseismic) data to estimate the dominant frequency value of the soil, which is an indicator of the local geotechnical conditions and soil dynamics.[24]

The HVSR (Horizontal-to-Vertical Spectral Ratio) method is still considered common because its results only characterize the soil type and the thickness of the sediment layer. The HVSR method produces an H/V curve that can be further processed using the Rayleigh wave ellipticity inversion method. The inversion process is performed using Dinver software, with the parameters vp (primary wave velocity), vs (shear wave velocity), Poisson's ratio, and density, all assumed to be constant at each measurement point.

Herak pada tahun 2008 mengembangkan sebuah metode berupa pemodelan balik (inverse modelling) untuk mengetahui litologi bawah permukaan suatu wilayah secara lebih spesifik. Salah satu metode dari pemodelan balik ini adalah metode kurva ellipticity, yang bertujuan untuk memperoleh parameter kecepatan gelombang geser permukaan (Vs) pada setiap titik pengukuran mikrotremor. Penyelesaian proses inversi sangat bergantung pada penentuan nilai parameter yang mendekati nilai data eksperimen. Dalam proses penyelesaian ini, dilakukan pengulangan (iterasi) untuk menilai tingkat keakuratan hasil inversi, yang dapat diamati dari nilai kesalahan (misfit). Semakin kecil nilai misfit, semakin baik profil kecepatan gelombang geser yang diperoleh.

Microseismic is a method in geophysics that utilizes low-amplitude natural vibrations that arise as a result of natural events, such as wind, ocean waves, or human activity.

Ambient noise, which is commonly detected in ground motion recordings, indicates that the ground is never completely at rest.[25] This phenomenon is caused by various sources of energy that generate seismic waves, such as ocean waves and the continuous variability of weather, indicating the presence of noise levels at any given time. The highly complex geological conditions in Indonesia require specialized studies to describe soil characteristics across various regions.[26,27] In addition, a representative database of dominant frequency values is needed to support disaster mitigation efforts and safer, more sustainable spatial and development planning.[28,29]

Therefore, the purpose of this research is to analyze the dominant frequency formation unit, amplification factor, and seismic vulnerability index and then the results are further analyzed with shear wave velocity in Garunglor Village. The analysis applied an interdisciplinary approach involving geology, environmental science, and physical science. The expected result of this research is a significant contribution to the development of more effective mitigation strategies, including sustainable spatial planning and early warning systems, as well as an important reference for development planners and related parties to reduce the risk of earthquake disasters in Garunglor Village, Sukoharjo District. The geological formations in Garunglor Village consist of 3 formations, namely the Ligung Formation breccia members, the Tread Formation breccia members, and the Tread Formation limestone members.

Methods

This research is located in Wonosobo, Sukoharjo District with data collection in Garunglor Village and its surroundings. The research used microtremor data from 14 measurement points. The measurement points covered the Garunglor area and measurements were taken around it as supporting data. The measurement points in the geological formation of limestone members of the tread formation were carried out 6 measurement points, breccia members of the ligung formation were carried out 7 measurement points, and in the formation of breccia members of the tread formation one measurement point was carried out. The following Figure 2 Map of research points based on their geological formations

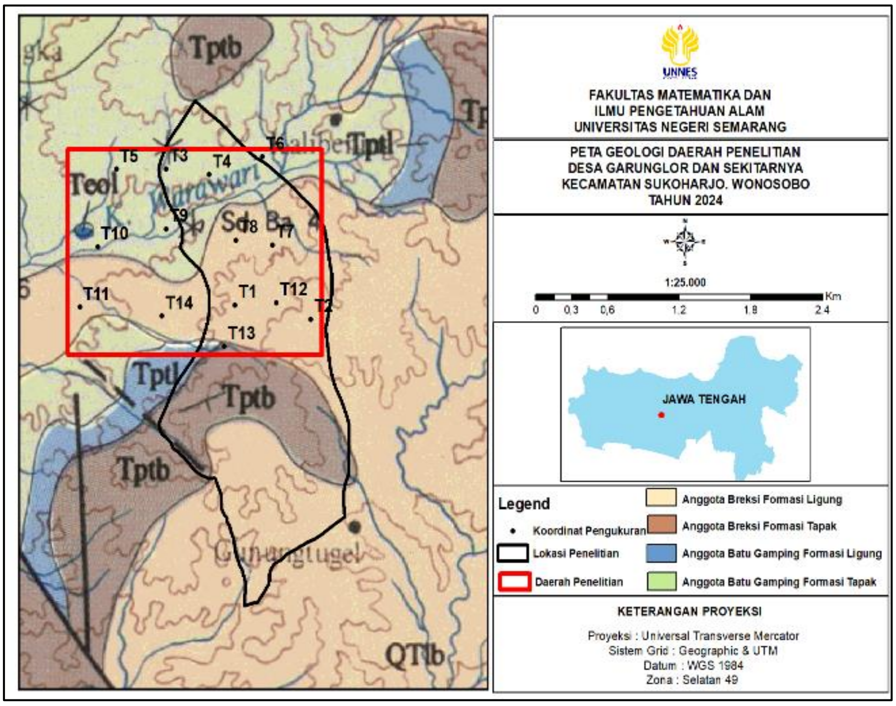


Figure 2. Geologic formations of the study area

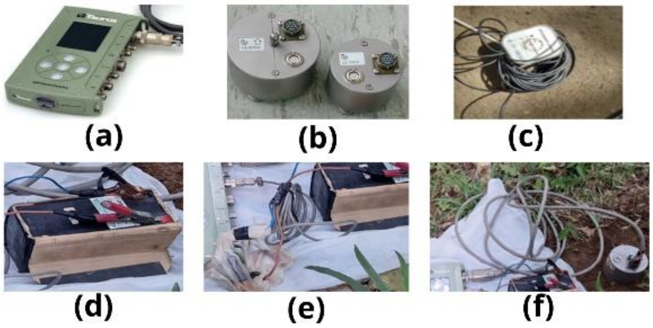


Figure 3. Research device tools
(a). Taurus brand digital portable seismograph, (b). Seismometer type LE-3Dlite, (c). GPS, (d). Accu (battery), (e). Digitizer connecting cable to power supply, (f). Digitizer to sensor connecting cable.

The ground amplification study was conducted at 14 observation points using hardware tools, including a Digital portable Seismograph brand Taurus and a Seismometer type LE-3Dlite, with a 30-minute measurement duration per measurement point, in accordance with the measurement operational standards of the SESAME European Research Project. Ambient wave observations were made for 30 minutes at 100 Hz, yielding 6000 data points per minute. The vibration source was taken from ambient vibrations around the observation site. The seismometer measured three wave components: the EW (east-west) component, the NS (north-south) component, and the vertical (up-down) component required for microseismic analysis.[30] Other equipment used includes a GPS, an Accu (battery), a connecting cable, and a laptop computer. The following tools were used to retrieve the data in Figure 3.

This microseismic study uses low-amplitude ambient vibrations originating from ground motion, wind, ocean waves, or vehicle vibrations. Microtremor observations are easy to conduct and can be applied in areas with high to low seismicity. The amplification factor of a site can be determined from the peak height of the HVSR spectrum of microtremor measurements at that site.[31] The dominant period or dominant frequency obtained from the HVSR curve correlates with the thickness of the sediment layer. Ambient vibrations captured by the seismometer are caused by vehicle movement, wind-induced vegetation movement, or hammer impacts on the ground. The seismometer captures vibration data, which is recorded by a seismograph. Ambient wave data from a single observation point are used to graph the relationship between H/V and wave frequency. The processing of microseismic data used the HVSR method with the help of Sessaray Geopsy software. The HVSR method is applied after noise is removed from the signal during the cutting process, yielding H/V curves, dominant frequency (f0), and amplification factor (A0) values. The classification of soil types and amplification factors provides a fundamental basis for evaluating local site effects and seismic vulnerability. According to Kanai (1983), the dominant frequency (f_0) is a key parameter that reflects the subsurface geological conditions, particularly the stiffness and thickness of sedimentary layers. Higher dominant frequencies are typically associated with hard rock or shallow bedrock, whereas lower frequencies indicate softer soils with thicker sediment accumulations.[40] As shown in Table 1

In addition to soil classification, the amplification factor (A_0) is another important parameter that describes the degree to which seismic waves are intensified due to local site conditions. According to BMKG (1998), amplification factors are categorized into four zones, as presented in Table 2.

Table 1. Dominant Frequency Soil Classification[40]

Soil Classification	Dominant Frequency (Hz)	Soil Classification	Soil Description
Type I	$6{,}7 \leq f0 < 20$	Tertiary or older rocks. Composed of hard sandy and gravelly materials	Thin surface sediment layer dominated by hard rock
Type II	$4 \leq f0 < 6{,}7$	Alluvial deposits about 5 m thick, consisting of sandy gravel, hard sandy clay, and loam	Surface sediment thickness categorized as medium, approximately 5–10 m
Type III	$2{,}5 \leq f0 < 4$	Alluvial deposits with sediment thickness >5 m, composed of sandy gravel, hard sandy clay, and loam	Surface sediment thickness categorized as thick, approximately 10–30 m
Type IV	$f0 < 2{,}5$	Alluvial deposits formed by delta sedimentation, consisting of topsoil and mud up to 30 m or more in depth	Surface sediment thickness categorized as very thick

Table 2. Classification of Factor Amplification (A0)[41]

Zone	Classification	Dominant Amplification Value
1	Low	$A < 3$
2	Moderate	$3 \leq A < 6$
3	High	$6 \leq A < 9$
4	Very High	$A \geq 9$

The basic principle of this method is the similarity between the ratio of horizontal to vertical spectra with wave transfer from bedrock to surface.[4] The dominant period and peak value of the ratio spectra (H/V) reflect the natural period and amplification factor of the soil layer.[32] The H/V value is obtained from the comparison of the Fourier amplitude spectrum of the horizontal wave component to the vertical wave. According to Nakamura in 1989 in[33] the H/V curve is obtained from the following equation:

$$HVSR = \frac{\sqrt{\left(A_{(U-S)}(f)\right)^2 + \left(A_{(B-T)}(f)\right)^2}}{\left(A_{(V)}(f)\right)} \tag{1.1}$$

Where:

HVSR = *Horizontal to Vertical Spectral Ratio*

$A_{(U-S)}(f)$ = The amplitude value of the North-South component frequency spectrum

$A_{(B-T)}(f)$ = The amplitude value of the West-East component frequency spectrum

$A_{(V)}(f)$ = The amplitude value of the Vertical component frequency spectrum.

According to Nakamura in[34] and [35] the seismic vulnerability index (Kg) is obtained by inputting the parameters of the dominant frequency value (f_0) and amplification factor (A_0) as follows:

$$K_g = \frac{{A_0}^2}{f_0} \tag{1.2}$$

where:

Kg = Seismic vulnerability index

A_0 = Factor amplification

f_0 = Dominant frequency.

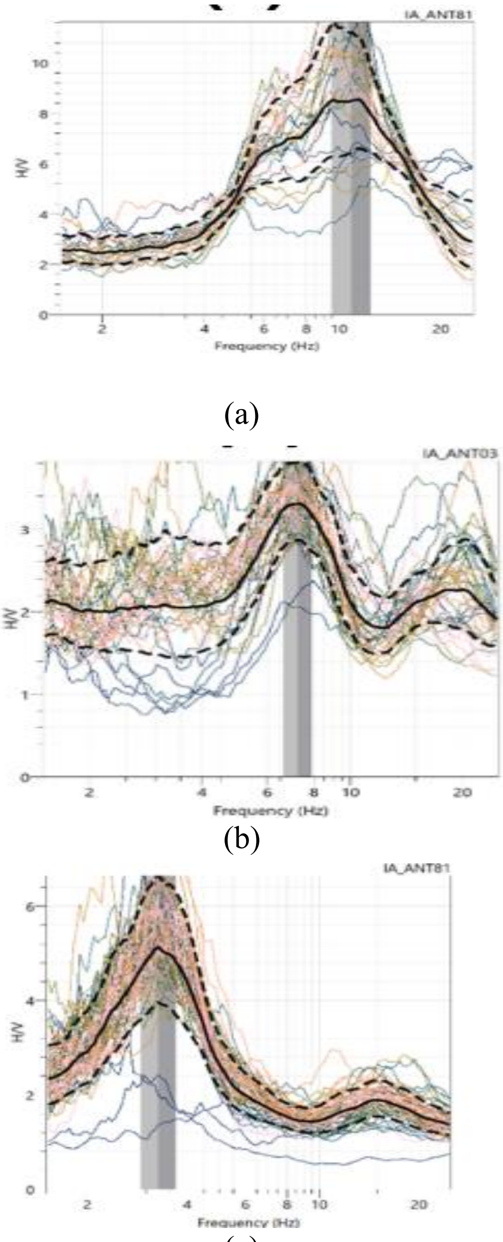
Table 3. HVSR analysis results

Formation	Point Name	F0	A0	Kg
Tptl (Ligung Formation–Limestone Member)	T13	10.8547	6.47959	9.863457
Tomt (Tapak Formation–Limestone Member)	T3	2.9883	6.48823	3.062612
	T4	13.2082	2.33036	2.32933
	T5	0.707494	3.32117	3.691119
	T6	5.44135	2.76302	0.577995
	T9	3.14222	3.20055	14.4786
	T10	7.22696	4.34837	3.474932
QTlb (Ligung Formation–Breccia Member g)	T1	13.7455	3.34389	1.729704
	T2	2.33139	2.54528	0.508489
	T7	6.46446	2.6517	2.237753
	T8	12.7406	3.30309	1.509681
	T11	5.13222	3.26928	2.082567
	T12	18.2853	1.71337	0.160546
	T14	4.20559	8.485	6.632631

Result and Discussion

Based on the results of ambient wave observations at 14 points using a seismometer, three wave components will be obtained, namely the NS (north-south), EW (east-west), and V (vertical) directions. The three components of ambient wave data are then processed using the HVSR method with the help of Arcgis software. Analysis using the HVSR method produces a graph showing the relationship between H/V and frequency. The soil amplification factor is obtained from the maximum H/V ratio at the dominant frequency (f0).

Table 1 shows the results of the H/V analysis at 14 observation locations.The following Figure 4 shows the HVSR curves generated from processing the microseismic data to obtain the dominant frequency (f_0) and amplification factor (A_0) values:



(a)

(b)

(c)

Figure 4. HVSR result curve (a). At QTlb Formation point T11, (b). At Tptb formation point T13, (c). Tomt formation point T10

Dominant frequency map distribution analysis is used to analyze vulnerable zones. Earthquake waves will be amplified if an area has a thick sedimentary layer. The thickness and sedimentary constituents of an area can be determined by the dominant frequency parameter.[37] The dominant frequency is related to the depth of the wave's reflected plane, which provides information about the boundary between the sedimentary layer and the bedrock layer. The thicker the depth of the sedimentary layer in an area, the smaller the dominant frequency value will be.

The relationship between the dominant frequency and soil susceptibility is inversely proportional. The lower the dominant frequency, the thicker the sediment layer. This is because seismic waves that are trapped in thick, soft sediments for a long time make areas with thick, soft sediment layers very easily damaged by seismic wave shocks. Conversely, if the dominant frequency is high, the area tends to have a low level of vulnerability due to its thin sediment layer and to be more compact.

In general, the distribution of f0 values in Garunglor Village and its surroundings, based on data processing results, ranges from 1.71 to 18.3 Hz, as shown in Figure 5.

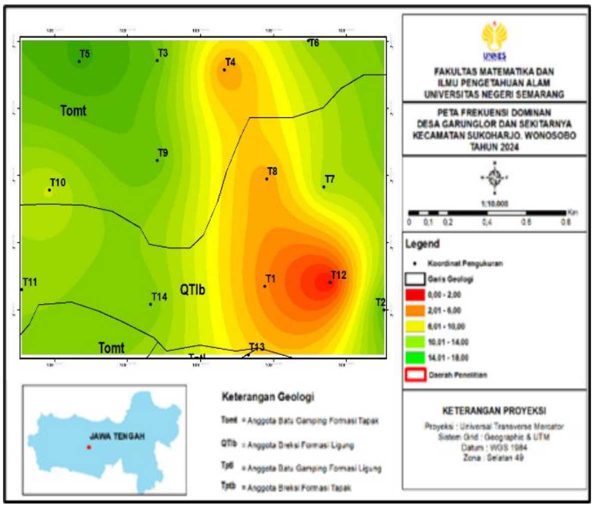


Figure 5. Dominant Frequency Map

At measurement points T3, T4, T5, T6, T9, and T10 with frequencies of 2.99, 13.2, 0.71, 5.4, 3.1, and 7.2 Hz respectively are areas located in limestone members of the tread formation (Tomt) where in the formation there is a point that has a low frequency level of 0.71 Hz at point T5 and also has a point where the frequency level is high at point T4 with a value of 13.2082 Hz. At point T13 has a high frequency of 10.8547 Hz in the limestone member of the ligung formation (Tptl). Measurement points T1, T2, T7, T8, T11, T12 and T14 are members of the ligung formation breccia (QTlb) with frequencies of 13.75, 2.3, 6.46, 12.74, 5.13, 18.28, and 4.21 Hz respectively, at point T2 has a low frequency of 2.33 Hz and also a high dominant frequency at point T12 with a value of 18.28.

According to Kanai, the high dominant frequencies at T1, T4, T8, T10, T12, and T13, with values ranging from 7.23 Hz to 18.28 Hz, indicate tertiary or older rocks. Consisting of hard sandy rocks, gravel with a thin sediment thickness, and dominated by hard rocks, the area around the research point, with a high dominant frequency value, is not potentially damaged during an earthquake due to seismic wave shaking. The low dominant frequency is at point T5, which, according to Kanai, is type IV with a very thick sedimentary layer; alluvial rocks formed from delta sedimentation, topsoil, and mud with a depth of 30 m or more are most likely to have the most serious impact during an earthquake. This statement is in accordance with the conditions in the field, as evidenced by Figure 6 below.

Figure 6. Landslide Location at Point T5

The amplification factor is a factor related to the strengthening of seismic waves, referring to the strengthening of seismic waves passing through certain materials, such as soil or rock.[25] This factor is important in understanding the identification of rock composition and how earthquake vibrations are amplified. The lower the amplification factor (A0) value, the harder the rock being passed through, while the greater the amplification factor (A0) value, the softer the rock being passed through.[38] Based on seismic engineering studies,[17] areas with softer lithology have a higher risk of damage during an earthquake. This is due to greater wave amplification in areas with soft materials than in areas with denser rock. In other words, areas with high amplification values tend to experience stronger shaking because they are composed of soft materials. Conversely, areas composed of hard materials have a lesser risk of damage due to their low amplification values. This condition is strongly influenced by local geological conditions.[21]

A decrease in rock density will increase the value of the amplification factor because soft sediments slow down the duration of wave propagation in the area and cause greater shaking to building structures.[32] Conversely, soft sedimentary rocks amplify ground motion during an earthquake, causing more damage than hard rock layers. The amplification factor is controlled by the impedance contrast between the soft layer and the bedrock.[31] Variations in the geological formations, thicknesses, and physical properties of soil and rock layers affect the amplification value. For example, deformed rocks can change their physical properties, and the presence of faults can also affect amplification.

Based on data processing in Garunglor village and its surroundings, the A0 value varies from 2.34 to 8.48, as shown in Figure 7.

Based on the processed data, the limestone members of the tread formation (Tomt), namely T3, T4, T5, T6, T9, and T10, have A0 values of 6.49, 2.33, 3.32, 2.76, 3.20, and 4.35, respectively. At points T1, T2, T7, T8, T11, T12, and T14, which are members of the ligung formation breccia (QTlb), have A0 values of 13.75, 2.33, 6.46, 12.74, 5.13, 18.28, and 4.21. At point T13, which is included in the member of the ligung formation limestone (Tptl), has an A0 value of 10.85. According to BMKG, the dominant amplicification classification of high A0 values with soft sediments is at measurement points T1, T13, and T14, with amplification values of 6.48, 8.48, and 6.48, which are limestone and sandstone, as shown in Figure 8.

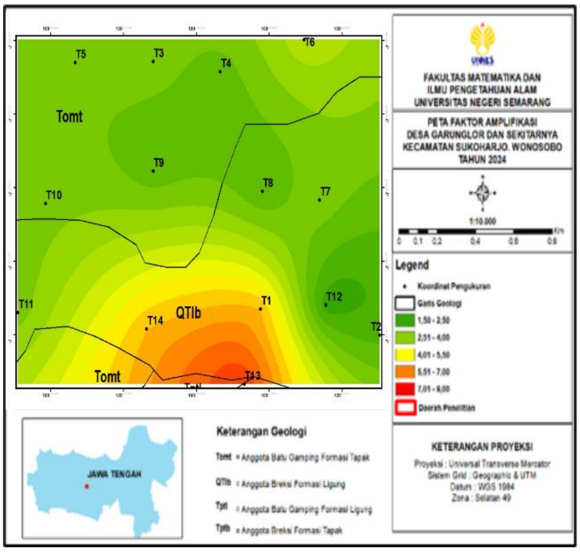


Figure 7. Map of Amplification Factor (A0) of Garunglor Village and its Surroundings

Figure 8. Limestone in the Tptl Formation

This condition is in accordance with the geological formations in the area, namely the limestone member of the Ligung formation (Tptl) at point T13 and the breccia member of the Ligung formation (QTlb) at points T1 and

T14. The limestone member of the ligung formation (Tptl), which is composed of limestone, sandstone, marl, and coral, is a material that is categorized as sedimentary material. Areas dominated by sedimentary materials are more likely to amplify during an earthquake.[39] This indicates that the areas in the study points tend to have more potential to experience resonance processes that result in strong shaking during an earthquake because they consist of softer surface layers. Amplification values with a medium classification are located at points T1, T5, T8, T9, T10, and T11 with values of 3.34, 3.32, 3.30, 3.20, 4.35, and 3.27, respectively, while low A0 values are located at measurement points T2, T4, T6, T7, and T12 with values of 2.54, 2.33, 2.76, 2.651 and 1.71, respectively. The low A0 value indicates that the subsurface layer in the formation is less likely to undergo wave resonance during an earthquake.

The seismic susceptibility index (Kg) describes the surface soil layer's susceptibility to deformation during an earthquake. Factors affecting the seismic susceptibility index include the presence of low-solidity sediments, while denser, more stable rocks are less likely to cause wave amplification. The seismic susceptibility index is highly dependent on the size of the amplification factor (A0). The higher the seismic vulnerability index value, the greater the potential for building damage during an earthquake.

The seismic susceptibility index can be used to describe an area's earthquake vulnerability because it reflects the deformation of soil layers induced by earthquakes. Areas with a high seismic susceptibility index are highly vulnerable to earthquakes. In general, high seismic susceptibility index values are found in areas with soft sedimentary layers. Conversely, areas with a low seismic susceptibility index indicate that the soil consists of strong, stable rocks, so the impact of earthquake shocks will be smaller. Based on the processed data, the seismic susceptibility index in Garunglor village and its surroundings ranges from 0.16 to 14.48, as shown in Figure 9.

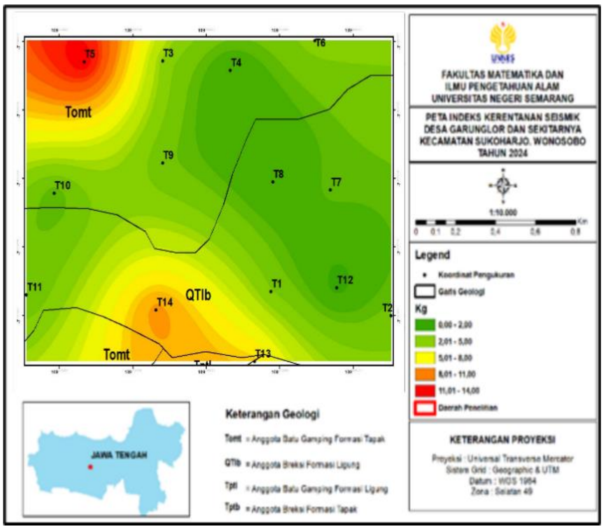


Figure 9. Map of Seismic Vulnerability Index (Kg) of Garunglor Village and its Surroundings

Based on the seismic susceptibility index (Kg) processing data in each formation, it is found that in the Tomt formation, points T3, T4, T5, T6, T9, and T10 have values of 3.06, 2.33, 3.69, 0.58, 14.48, and 3.48, respectively. In the QTlb formation, points T1, T2, T7, T8, T11, T12, and T14 have Kg values of 1.729704, 0.51, 2.24, 1.51, 2.08, 0.16, and 6.63, respectively. As for the Tptl formation, point 13 has a value of 9.86.

The highest Kg values are at points T5, T14, and T13, with values of 14.48, 9.86, and 6.63, respectively. The results obtained show that points T5, T14, and T13 are areas with soft sediments and are highly vulnerable. Points T2, T4, T7, T8, T9, T10, T11, and T12 have low seismic vulnerability index values of 2.33, 0.58, 1.73, 0.51, 2.24, 1.51, 2.08, and 0.16. The lowest seismic vulnerability index value is 0.16 at point T12.

The analysis of the dominant frequency (F_0), amplification factor (A_0), and seismic vulnerability index (Kg) in the study area demonstrates a strong correlation between local geological conditions and the potential seismic response. Variations in the dominant frequency indicate differences in the thickness and stiffness of the sedimentary layers. Areas with low dominant frequency values are generally associated with thick, soft sediments, which tend to amplify long-period seismic waves. In contrast, higher dominant frequencies correspond to thin sediment layers overlying hard bedrock, indicating more stable ground conditions with lower earthquake resonance potential.

Similarly, the amplification factor values reflect the degree of seismic wave strengthening as they propagate through different geological materials. Regions composed of soft sedimentary or weathered materials typically exhibit higher amplification, while areas underlain by compact, dense rocks tend to have lower amplification. These differences highlight the importance of the impedance contrast between the surface and subsurface layers, which controls the extent of ground motion during seismic events.

The seismic vulnerability index, which combines both the effects of amplification and dominant frequency, provides a quantitative representation of the surface's susceptibility to seismic deformation. Areas with high vulnerability index values indicate zones with soft sediments and strong amplification, suggesting a higher likelihood of ground shaking and structural damage during an earthquake. Conversely, zones with low vulnerability index values represent geologically stable regions with dense subsurface materials, which are relatively safer from seismic impacts.

From a mitigation perspective, understanding the spatial distribution of these parameters is essential for reducing earthquake risk and for land-use planning. Regions characterized by high amplification and vulnerability should be prioritized for mitigation measures such as strengthening building structures, implementing stricter construction standards, and designating them as zones with limited development. Meanwhile, areas with lower vulnerability levels can be utilized for critical infrastructure and relocation purposes. Therefore, integrating the analysis of $f0$, A0, and Kg into seismic microzonation studies provides a scientific foundation for developing effective earthquake disaster mitigation strategies and sustainable regional planning.

Conclusion

Garunglor village and the surrounding area of Sukoharjo sub-district, Wonosobo Regency, have a dominant low-frequency distribution, indicating that this area has a thick sedimentary layer composed of alluvial rocks from delta sedimentation, topsoil, and mud. In the Tomt formation, points T3, T4, T5, T6, T9, and T10 have dominant frequency values of 2.99, 13.21, 0.71, 5.44135, 3.14, and 7.23. The QTlb formation at points T1, T2, T7, T8, T11, T12, and T14 has dominant frequency values of 13.75, 2.33, 6.46, 12.74, 5.13, 18.28, and 4.21, respectively. Point T13 is in the Tptl formation with a value of 10.85 Hz. The high dominant frequency at T1, T4, T8, T10, T12, and T13 ranges from 7.23 Hz to 18.28 Hz; the area around the research point with a high dominant frequency indicates thin sediment and a hard-rock-dominated environment. The low dominant frequency at points T2 and T5 indicates that the sediment surface is very thick at those points.

The amplification value of Garunglor Village and its surroundings is dominated by low classification, indicating a low risk of building damage during an earthquake. At points T3, T4, T5, T6, T9, and T10, including members of the tread formation limestone (Tomt), have A0 values of 6.49, 2.33, 3.32, 2.76, 3.20, and 4.35, respectively. At points T1, T2, T7, T8, T11, T12, and T14, which are members of the ligung formation breccia (QTlb), have A0 values of 13.75, 2.33, 6.46, 12.7406, 5.13, 18.28, and 4.21. At point T13, which is included in the limestone member of the Ligung formation (Tptl), has an A0 value of 10.8547. Low A0 values are at measurement points T2, T4, T6, T7, and T12 with values of 2.55, 2.33, 2.76, 2.65, and 1.71, respectively. The low A0 value indicates that the subsurface layer in the formation is less likely to undergo wave resonance during an earthquake. Amplification values with medium classification are located at points T1, T5, T8, T9, T10, and T11 with values of 3.34, 3.32, 3.30, 3.20, 4.35, and 3.27, while the dominant amplification with high A0 values is at measurement points T1, T13, and T14 with amplification values of 6.48, 8.48, and 6.48 which are limestone and sandstone. The medium and high amplification values indicate that the study points are more likely to experience resonance processes that result in strong shaking during an earthquake because they are underlain by softer surface layers.

The seismic vulnerability index (Kg) in Garunglor Village and its surroundings is high, with values of 14.48, 9.86, and 6.63 at points T5, T14, and T13, respectively. The results show that at that point, there is an area with a high level of vulnerability. Points T2, T4, T7, T8, T9, T10, T11, and T12 have low seismic vulnerability index values of 2.33, 0.58, 1.73, 0.51, 2.24, 1.51, 2.08, and 0.16, indicating that the area is not vulnerable and can be occupied. The lowest seismic vulnerability index value is 0.160546 at point T12. At that point, it is well-suited for use as a relocation area.

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