



# Analysis of the Subsurface Structure Using the HVSR Method in Jorong Air Putih Lima Puluh Kota Regency

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**Abstract:** This study aims to analyze the subsurface structure and soil stability in Jorong Air Putih, Lima Puluh Kota Regency, West Sumatra, using the Horizontal to Vertical Spectral Ratio (HVSR) method. This area is prone to landslides due to its steep topography, complex geological conditions, and high seismic activity, so a subsurface study is needed as a disaster mitigation measure. Microtremor surveys were conducted at 18 measurement points, and the data were analyzed using Easy HVSR software to obtain seismic parameters, namely dominant frequency ( $F_0$ ), amplification factor seismic ( $A_0$ ), vulnerability index (Kg), and estimated shear wave velocity ( $V_s$ ). The analysis results showed a dominant frequency of 0.4–10.6 Hz, an amplification factor of 1.22–3.20, and  $V_s$  of 175–700 m/s. These values reflect lithological variations from soft sediments to hard rocks, with most areas having low vulnerability, but there are points with moderate vulnerability levels. These findings indicate that areas with low  $V_s$  and high  $A_0$  have the potential to experience seismic wave amplification and are more prone to landslides. The research gap lies in the limited integration of HVSR data with geotechnical parameters and long-term monitoring. In practical terms, the results of this study can be used as a basis for spatial planning, earthquake-resistant infrastructure development, and disaster mitigation strategies in landslide-prone areas in Lima Puluh Kota Regency.

**Keywords:** HVSR, Jorong Air Putih, Landslide, Microtremor, Shear Wave velocity, Subsurface Structure



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## 1. Introduction

The island of Sumatra is located in an area of high tectonic activity because it lies in the collision zone between the Eurasian Plate to the north and the Indo-Australian Plate to the south. In the subduction zone off the west coast of Sumatra, the Indo-Australian Plate moves beneath the Eurasian Plate, which is the main source of tectonic activity in this region. This process forms an active volcanic arc that triggers intense volcanic activity and earthquakes. One of the most

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significant tectonic structures is the Sumatra Fault, which runs parallel to the west coast for more than 1,900 km and consists of a number of active segments that cause major earthquakes in the region [1]

The province of West Sumatra has very complex geological conditions, characterized by the presence of mountains and steep valleys formed by active tectonic processes over a long geological period [2]. This tectonic activity makes the region prone to various geological disasters, especially landslides. Landslides are related to the geological characteristics and structure of the subsurface [3]. Lima Puluh Kota Regency, particularly Jorong Air Putih, is one of the areas with a high risk of landslides due to its steep topography, unstable surface contours, and rock lithology that is relatively susceptible to weathering. This vulnerability is exacerbated by high seasonal rainfall intensity and increased human activity, such as heavy vehicle traffic on main transportation routes, which contributes to a decline in slope stability. These conditions emphasize the importance of a deeper understanding of subsurface characteristics, particularly sediment thickness, rock type, and shear wave velocity ( $V_s$ ), which are key indicators of soil strength and stability.

The province of West Sumatra is one of the regions in Indonesia that is highly prone to landslides. Based on monitoring by the Geological Agency, Volcanology and Geological Disaster Mitigation Center in August 2015, nationally, areas prone to landslides are classified as having medium to high vulnerability. In 2011, there were 21 landslide events recorded in West Sumatra, spread across several districts. The high potential for disasters is influenced by factors such as intense rainfall, steep slopes with a gradient of more than  $70^\circ$  (100-150%), and the characteristics of the region, which is classified as a red zone prone to landslides [4].

Tectonically, Jorong Air Putih is directly affected by the Sumatra Fault, which causes rock deformation in the form of cracks, folds, and faults, thereby impacting slope stability. Its lithology consists of Tms2 units, namely Tertiary sedimentary and volcanic rocks with soft to moderately dense properties, making them relatively susceptible to erosion. The steep topography combined with high rainfall in West Sumatra increases the potential for pore water pressure accumulation, which can ultimately trigger landslides. Recent studies indicate that landslides remain the dominant natural disaster in West Sumatra, causing significant socio-economic impacts.

The microtremor method is a non-destructive geophysical approach that utilizes small-amplitude harmonic vibrations from natural and artificial sources [5]. Microtremor analysis using the Horizontal to Vertical Spectral Ratio (HVSr) method is widely used because it is simple, economical, and environmentally friendly [6]. This method produces key parameters such as dominant frequency ( $F_0$ ) and amplification factor ( $A_0$ ), as well as derivative parameters such as seismic vulnerability index ( $K_g$ ) that can be used to identify potential seismic wave amplification and soil vulnerability to shocks [7]. In the last decade, the HVSr method has proven to be effective in seismic vulnerability studies and subsurface geological characterization in various disaster-prone areas.

However, HVSr-based geophysical research in Jorong Air Putih, Lima Puluh Kota Regency, is still very limited. The available geological and geomorphological information is generally regional in nature and has not specifically examined subsurface characteristics for the purpose of landslide mitigation. This research gap highlights the need for microtremor-based geophysical studies to obtain a more detailed picture of the subsurface structure, sediment thickness, and seismic vulnerability of the area. Based on this background, this study aims to analyze the subsurface structure and soil stability in Jorong Air Putih using the HVSr method. The results of this study

are expected to contribute to disaster mitigation efforts, spatial planning, and sustainable infrastructure development in landslide-prone areas in West Sumatra.

## 2. Materials and Method

The basic concept of the Horizontal to Spectral Vertical (HVSr) method is based on the principle that the spectral ratio between the horizontal and vertical components of seismic waves reflects the wave transfer response from the bedrock to the surface (Nakamura, 1989). This method utilizes the phenomenon of local resonance that occurs due to differences in seismic impedance between soft sediment layers and harder bedrock. According to Nakamura, the main characteristics obtained from the H/V ratio curve are the dominant frequency or period, the value of the dominant period, and peak H/V ratio ( $A_0$ ), which respectively represent the natural frequency and amplification factor of the soil layer above the bedrock. The H/V ratio is calculated by comparing the amplitude of the Fourier spectrum of the horizontal component (average of two horizontal directions) to the vertical component of the microtremor wave recorded during the measurement process.

The Horizontal to Vertical Spectral ratio (HVSr) method is often used to analyze very small amplitude ground vibrations (microtremors), enabling a deeper understanding of the amplitude of ground vibrations in the horizontal (sideways) and vertical (upward) direction to determine soil properties, such as sediment layer thickness and natural soil frequency [8]. This ratio analysis enables the identification of subsurface structures, particularly in describing differences in density and strength of soil layers to a certain depth. By combining the microtremor method and HVSr analysis, more detailed information about subsurface geological conditions can be obtained. Additionally, the HVSr method is used to determine the amplification factor ( $A_0$ ) and dominant period or dominant frequency ( $f_0$ ) at a location, which are assumed based on the peak of the HVSr curve. These values are obtained through data processing using the Easy HVSr software. The figure below shows the map of the research site location in Jorong Air Putih.

The seismic vulnerability index is an important parameter in assessing the extent to which an area responds to shocks caused by seismic activity. The seismic vulnerability index ( $K_g$ ) is a tool for assessing the susceptibility of a certain location to harm from ground movement. Both the dominant frequency and the amplification value affect the  $K_g$  value. Additionally, there is a direct relationship between the  $K_g$  value and sediment thickness, where a higher  $K_g$  value indicates thicker sediment layers, and conversely, a lower  $K_g$  value indicates relatively thin sediment layers in the area [9]. According to [10], The seismic vulnerability index is a numerical representation of a region's susceptibility to earthquakes, as determined by the properties of the rocks present in that location. The low density of the sediment layer is one of the key elements impacting this value. By comparing the amplification factor with the dominant frequency, the seismic vulnerability index value can be determined using the following formula:

$$K_g = \frac{A_0^2}{f_0} \quad (1)$$

Table 1. Classification of seismic vulnerability index sites[11]

| Zone | Calssification | Amplification value |
|------|----------------|---------------------|
| 1    | Low            | $A_0 < 3$           |
| 2    | Medium         | $3 \leq A_0 < 6$    |
| 3    | High           | $6 \leq A_0 < 9$    |
| 4    | Very high      | $A_0 \geq$          |

Variations in shear wave velocity can provide a more detailed explanation of the structure of rock layers beneath the surface, which are obtained from forward calculations and inversion of H/V spectral ratio (HVSr) data on microtremors. Rocks with hard, dense, and massive characteristics, such as igneous rocks, tend to have a low susceptibility to landslides. Conversely, soft, non-solid, and easily eroded rock types such as clay, silt, and shale have a higher susceptibility to landslides. The type of rock-forming material, identified based on shear wave velocity ( $V_s$ ) values, generally corresponds to the soil type commonly found at past landslide sites. In addition to geological factors, the potential for landslides or soil movement is also influenced by slope gradient, vegetation cover, slope stability, and rainfall intensity [12].

Table 2. Site classification is determined by  $V_s$  values from soil investigation results and SNI 1726 laboratory. (Badan Standarisasi Nasional, 2012)

| Site classification           | Shear wave velocity $V_s$ (m/s) |
|-------------------------------|---------------------------------|
| Hard rock                     | $V_s \geq 1500$                 |
| Rock                          | $750 < V_s \leq 1500$           |
| Very dense soil and soft rock | $350 < V_s \leq 750$            |
| Moderate soil                 | $175 < V_s \leq 350$            |
| Soft soil                     | $V_s < 175$                     |

The approach of this study is descriptive and qualitative, this article aims to identify the subsurface structure and analyze soil stability using the Horizontal to Vertical Spectral Ratio (HVSr) method. The research location is in Jorong Air Putih, Lima Pulu Kota Regency, West Sumatra Province. Data was collected from 18 measurement points with an inter-point distance of  $\pm 400$  meters. At each point, microtremor data was recorded for approximately 30 minutes. The data was collected by means of a Sysmatrack-M.AE system and a 3-component S3S seismometer that was tied into it. The position and orientation of the device were assisted by GPS and compass devices. The data obtained was then recorded and analyzed using Easy HVSr, Google Earth, QGIS, and Microsoft Excel software.



Figure 1. Location of the research sites

Data collection was carried out by recording microtremors, which are natural ground vibration signals originating from non-artificial sources. In order to create HVSR curves, the acquired signals were transformed from the time domain to the frequency domain using Fourier transformation. This curve is analyzed to obtain the dominant frequency value ( $f_0$ ), amplification factor ( $A_0$ ), seismic vulnerability index ( $K_g$ ), and shear wave velocity ( $V_s$ ). The  $V_s$  velocity is calculated using a formula based on the thickness and  $V_s$  value of each layer.

Through microtremor data collection activities, results were obtained in the form of microtremor wave recordings on the horizontal and vertical planes, covering the East-West, North-South, and Vertical directions, as well as coordinate data from each measurement point. Next, the field measurement data was processed using Easy HVSR software. The process began with importing the field data, then selecting the HVSR (H/V) analysis method. At the calculation parameter setting stage, the smoothing type was set to 50.00. The frequency sampling range was also adjusted, from 0.50 Hz to 10.00 Hz. The data processing results yield the HVSR parameters, namely amplification ( $A_0$ ) and dominant frequency ( $f_0$ ). A total of 18 data points were collected for each parameter, then entered into Microsoft Excel to calculate additional parameters, namely the vulnerability value ( $K_g$ ), and used to estimate the shear wave velocity ( $V_s$ ) based on the dominant frequency results and local geological information.

### 3. Results and Discussion

#### 3.1 Dominant Frequency ( $f_0$ )

Dominant frequency can be used to describe the subsurface characteristics of an area. The presence of hard rock is indicated by a high dominant frequency value, while the presence of soft soil layers is indicated by a low value. [14]. At the research site in Jorong Air Putih, between 0.4 Hz and 10.6 Hz, the dominant frequency value ( $f_0$ ) fluctuates. Based on the Kanai classification, the soil in this area is grouped into four types: I, II, III, and IV. The frequency values ( $f_0$ ) that are

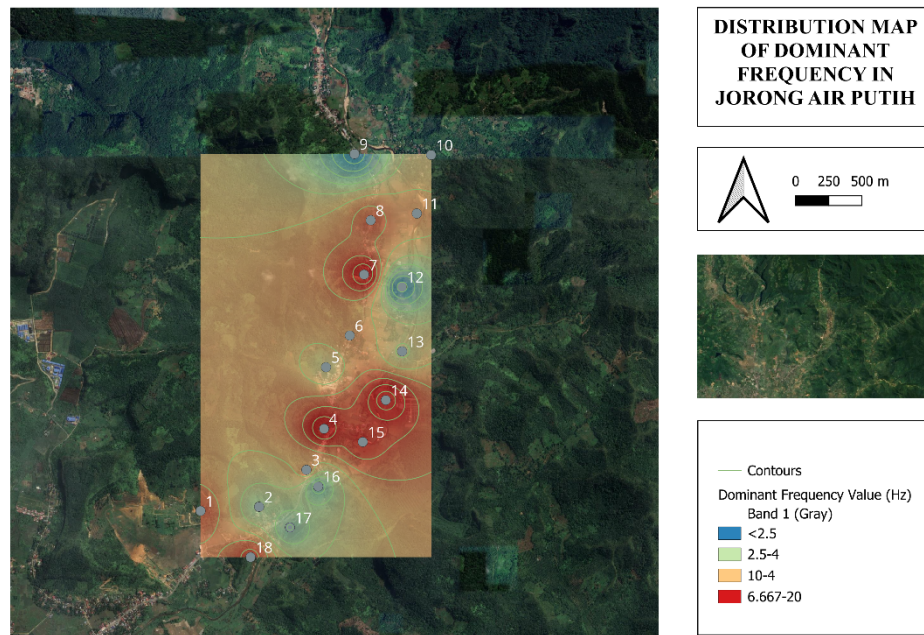
dominant are within the range of 2.5 Hz to 4 Hz are classified as type III, while very low values, between 0.4 Hz and 2.45 Hz, are categorized as type IV. Conversely, high dominant frequency values, ranging from 8.35 Hz to 10.6 Hz, fall under Type I classification.

The dominant frequency is influenced by the depth of the soil layer and the value of shear wave velocity ( $V_s$ ). To obtain the  $V_s$  value, microtremor data inversion is required. The  $V_s$  value obtained can then be used to determine the thickness of each soil layer and estimate the depth of the bedrock [15]. Geological characteristics with high  $V_s$  values generally indicate stable conditions and resistance to geodynamic disturbances, such as weathering or soil displacement. Dominant frequency analysis ( $f_0$ ) findings show that thick sedimentary layers dominate the research region and that bedrock is found at a great depth over much of the area.

A dominant frequency map is a map that shows the distribution of the most frequently occurring frequency values, reflecting the rock conditions in an area based on the type and properties of the rocks. The frequency values on this map are closely related to the thickness and depth of soft sediment layers beneath the surface. The higher the dominant frequency value, the thinner the sedimentary rock layers in the area tend to be and the higher their hardness. A dominant frequency map illustrates the distribution of frequency values through color variations, where each color represents a category of high, medium, or low frequency values. These values are grouped based on the dominant frequency classification table.

Table 3. Soil classification based on dominant values Jorong Air Putih

| Research point                        | Natural frequency (Hz) | Soil type | Sediment depth |
|---------------------------------------|------------------------|-----------|----------------|
| T1, T4, T14, T15, T18                 | 7.9 – 10.6             | I         | Very Thick     |
| T17                                   | 2.95                   | III       | Currently      |
| T9, T12, T16                          | 0.4 – 2.45             | IV        | Thin           |
| T2, T3, T5, T6, T7, T8, T10, T11, T13 | 4 – 9.85               | II        | Thick          |

Figure 2. Map of  $f_0$  value distribution

### 3.2 Amplification ( $A_0$ )

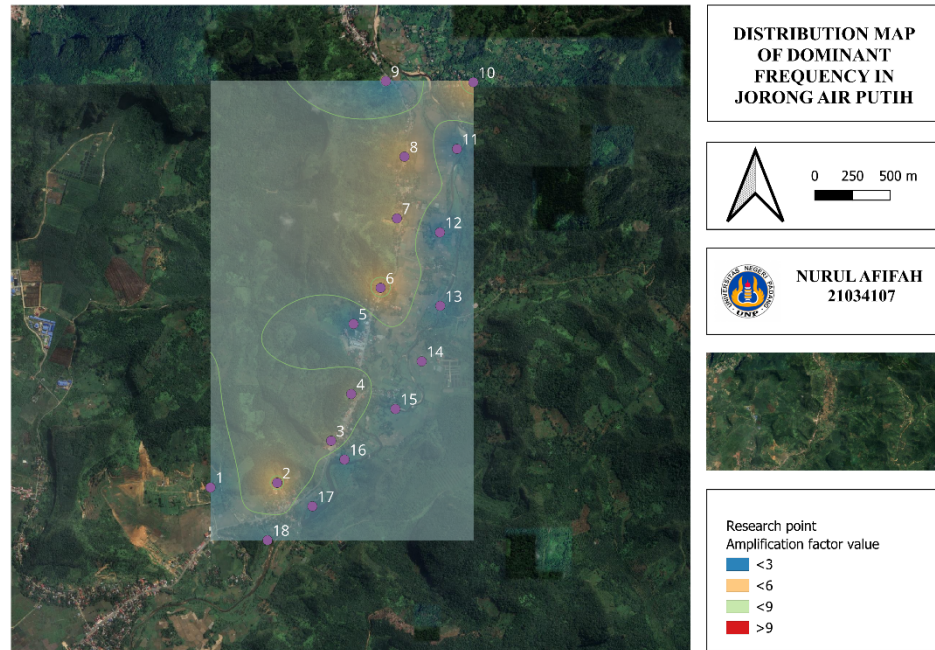
The shear wave velocity ( $V_s$ ) plays a role in influencing the amplification factor, with a lower  $V_s$  value resulting in a higher amplification factor. The density of the rock is a significant factor in the amplification factor, as indicated by this. As the rock density decreases, the amplification factor tends to increase [16]. The amplification factor is the ratio between the maximum acceleration of seismic waves at the ground surface and that occurring in the bedrock. If we know the impedance differential between the bedrock and the top layer of sediment, we may estimate this amplification value. The amplification value of waves reaching the surface is directly proportional to the magnitude of the impedance difference between the two layers [17].

In this study, the amplification factor values in the Jorong Air Putih area ranged from 1.22 to 3.20, with most measurement points falling into the low classification. However, there were several points with amplification values above 3, ranging from 3.11 to 3.20, which fell into the moderate classification. Based on this data, areas with moderate amplification values indicate the potential for vibration amplification due to dynamic soil activities, such as groundwater flow, saturation caused by rainfall, or slope stability disturbances. In extreme conditions, these factors can trigger landslides.

An amplification map is a map that shows the distribution of seismic wave amplification levels caused by significant differences between rock layers. Seismic waves tend to amplify when passing through a softer medium than the previous one. Generally, this map illustrates the distribution of soft and hard rock conditions based on the magnitude of amplification values. The higher the amplification value, the stronger the indication that subsurface rocks have undergone excessive deformation due to geological events that affect their physical properties.

Table 4. Amplification factor value ( $A_0$ ) in Jorong Air Putih

| Research point                                                           | Amplification factor value | Classification |
|--------------------------------------------------------------------------|----------------------------|----------------|
| T1, T3, T4, T5, T7, T8, T9,<br>T11, T12, T13, T14, T15,<br>T16, T17, T18 | 1.22 – 2.96                | Low            |
| T2, T6, T10                                                              | 3.2 – 3.13                 | Medium         |

Figure 3. Amplification factor value ( $A_0$ )

### 3.3 Seismic Vulnerability Index ( $K_g$ )

The results of the study show that the seismic vulnerability index ( $K_g$ ) in the Jorong Air Putih area, Lima Puluh Kota Regency, varies between 0.28 and 4.029. This range of values was obtained from the processing of microtremor data at 18 measurement points spread across various morphological and geological conditions. The  $K_g$  index is calculated based on dominant frequency parameters and amplification factors, which represent the dynamic response of the soil to seismic vibrations. Based on the analysis results, most measurement locations fall into the low vulnerability category, except for point T9, which shows a higher  $K_g$  value and is classified as an area with moderate vulnerability. This finding indicates the presence of variations in subsurface physical properties that warrant attention in the context of disaster mitigation.

The spatial distribution of the  $K_g$  index, visualized in the form of a map, shows that areas with high vulnerability tend to be located in areas with significant sediment layer thickness and high levels of softness. These conditions enable seismic wave amplification, where earthquake wave energy increases as it propagates through soft sedimentary material. As a result, the amplitude of seismic waves at the surface becomes larger, which can trigger geodynamic impacts such as landslides or damage to buildings standing on them. Therefore, high  $K_g$  values can be used as an important indicator in identifying high-risk areas for seismic disasters.

The soil vulnerability index ( $K_g$ ) map is a map that shows the distribution of vulnerability index values, which are related to the potential of an area to be affected by earthquake risks [18]. This index describes how vulnerable the surface soil layer is to excessive deformation during an earthquake. Severe damage caused by earthquakes generally occurs in alluvial plains consisting of thick sediment layers. Mathematically, soil vulnerability values ( $K_g$ ) are influenced by amplification values, which are directly proportional, and dominant frequencies, which are inversely proportional. The level of vulnerability of an area to earthquake shaking can be determined by the combination of these two parameters.

Table 5. Classification of seismic vulnerability index

| Research point                                                              | Value $K_g$ | Classification | Formation |
|-----------------------------------------------------------------------------|-------------|----------------|-----------|
| T1, T2, T3, T4, T5, T6, T7, T8, T10, T11, T12, T13, T14, T15, T16, T17, T18 | 0.2 – 2.4   | Low            | Alluvial  |
| T9                                                                          | 4.096       | Medium         | Alluvial  |

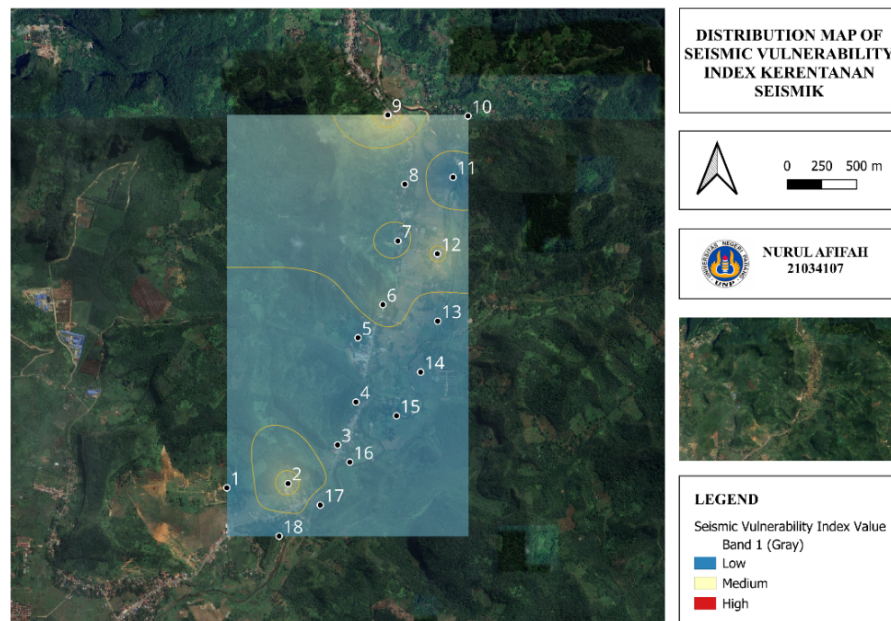


Figure 4. Map of seismic vulnerability index values

### 3.4 Shear Wave Velocity ( $V_s$ )

The results of the inversion process of the H/V curve, amplification factor ( $A_0$ ), and dominant frequency ( $f_0$ ) produce geophysical parameters in the form of primary wave velocity ( $V_p$ ), shear wave velocity ( $V_s$ ), and estimates of subsurface layer depth. The  $V_s$  value obtained is very important in identifying the characteristics of soil and rock layers at a location. The results indicate that  $V_s$  values can be categorized into four main categories based on the hardness and density characteristics of the constituent materials.

The first category reflects soft soil, with an average shear wave velocity of around 175 m/s. the low density of this soil tends to amplify seismic waves. The second category is classified as medium soil with a  $V_s$  velocity range between 250 m/s and 300 m/s. This soil has greater cohesion than soft soil, but deformation can still occur during strong vibrations. The third category consists of soft rock with a  $V_s$  value between 350 m/s and 450 m/s. The material in this layer generally consists of moderately weathered rock, resulting in more stable mechanical properties. Meanwhile, the fourth category is a layer with very dense material, such as hard soil to hard rock, with a  $V_s$  value between 500 m/s and 750 m/s. This type of material generally dominates deeper layers and has a higher ability to dampen the propagation of seismic waves.

This classification refers to the  $V_s$  value profile, presented in Table 4, which serves as a reference in interpreting subsurface conditions based on seismic parameters. Thus,  $V_s$  analysis not only provides an overview of the local geological structure, but also forms the basis for assessing the seismic vulnerability of an area to earthquake hazards.

Table 6. Classification value of shear wave velocity in Jorong Air Putih

| Research point                                                                                 | Value         | Classification | Layers |
|------------------------------------------------------------------------------------------------|---------------|----------------|--------|
| T1, T2, T3, T4,<br>T5, T6, T7, T8,<br>T9, T10, T11,<br>T12, T13, T14,<br>T15, T16, T17,<br>T18 | 175 – 210 m/s | Medium Soil    | 1      |
| T1, T3, T4, T5,<br>T6, T7, T8, T9,<br>T10, T11, T12,<br>T13, T14, T15,<br>T16, T17, T18        | 200 – 350 m/s | Medium Soil    | 2      |
| T2                                                                                             | 400 – 500 m/s | Solid Ground   |        |
| T1, T2, T3, T4,<br>T5, T6, T7, T8,<br>T9, T10, T11,<br>T12, T13, T14,<br>T15, T16, T17,<br>T18 | 415 – 600 m/s | Solid Ground   | 3      |
| T8, T13, T16                                                                                   | 200 – 300 m/s | Medium Soil    |        |
| T1, T3, T4, T5,<br>T6, T7, T9, T10,<br>T11, 12, T14,<br>T15, T17, T18                          | 350 – 700 m/s | Solid Ground   | 4      |
| T2                                                                                             | 750 – 800 m/s | Rocks          |        |

The classification results of shear wave velocity ( $V_s$ ) are the basis for this, it can be concluded that this parameter provides a significant and comprehensive description of the level of compactness, hardness, and stability of the subsurface layer. Layers with relatively low  $V_s$  values,

such as those in the soft soil and medium soil categories, are generally composed of loose and less dense materials. These characteristics result in low stability levels, making them more susceptible to deformation or soil movement when triggered by external factors such as earthquakes, heavy rainfall, or steep topography. This situation makes areas with low  $V_s$  values high-risk zones for geological disasters, particularly landslides and liquefaction.

Conversely, layers with high  $V_s$  values, such as those in the soft to hard rock categories, indicate better material density and cohesion. This condition reflects relatively high geomechanical stability, where the layer is able to withstand external forces more effectively. Therefore, areas with high  $V_s$  values tend to have a lower risk of landslides, especially if there are no morphological disturbances or excessive anthropogenic activities. The interpretation of  $V_s$  values obtained through the HVSR (Horizontal to Vertical Spectral Ratio) data inversion process is not only important for understanding subsurface geological conditions, but also serves as a vital tool in assessing a region's vulnerability to geotechnical disasters. This information can be utilized in various aspects of planning, such as spatial planning, determining the location of infrastructure development, and formulating strategies for mitigating natural disaster risks. Thus,  $V_s$  analysis serves as a scientific basis for supporting decision-making that prioritizes safety, sustainability, and disaster risk reduction in regions that are geologically prone to hazards.

#### 4. Conclusion

This study successfully identified subsurface characteristics and seismic vulnerability levels in Jorong Air Putih through HVSR microtremor analysis. The results show that the subsurface layer consists of soft sediments covering harder rocks, with dominant frequency ( $F_0$ ) and amplification factor ( $A_0$ ) values serving as important indicators of local seismic response. These conditions confirm that local geology plays a major role in amplifying earthquake shocks. In practical terms, the findings of this study make a real contribution to disaster mitigation in the Jorong Air Putih area. Information on seismic vulnerability can be used as a basis for spatial planning, determining earthquake-resistant building construction standards, compiling disaster risk maps, and increasing community preparedness. Thus, this research is not only beneficial from an academic perspective but also plays a crucial role in earthquake risk reduction efforts at the local level.

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