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Application of the HVSR Method to Evaluate Seismically Induced Slope Instability Potential in Sukorejo Village, Pugung District, Tanggamus Regency, Indonesia

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Abstract. This study evaluates seismically induced slope-instability potential in Sukorejo Village, Pugung District, Tanggamus Regency, Indonesia, using Horizontal-to-Vertical Spectral Ratio (HVSR) parameters: predominant frequency (f_0), amplification factor (A_0), shear strain (γ), and seismic vulnerability index (K_g). The results show that zones F3-E3 to D5 have high amplification (A_0), low predominant frequency (f_0), elevated shear strain, and the highest K_g values. These conditions indicate thick, soft, and poorly consolidated sedimentary layers with strong impedance contrast and high susceptibility to seismic shaking. Geological interpretation shows that the most vulnerable zones coincide mainly with the Hulusimpang formation (Tomh), whereas areas underlain by the Gunungkasih Complex (Pzg) are relatively more stable. Overall, the F3-E3-D5 zone is classified as highly susceptible to earthquake-triggered landslides, the D3-F4-H3 zone as moderately susceptible, and the remaining areas as relatively low risk.

Abstrak. Penelitian ini mengevaluasi potensi ketidakstabilan lereng akibat gempa di Desa Sukorejo, Kecamatan Pugung, Kabupaten Tanggamus, Indonesia, menggunakan parameter Horizontal-to-Vertical Spectral Ratio (HVSR), yaitu frekuensi dominan (f_0), faktor amplifikasi (A_0), regangan geser (γ), dan indeks kerentanan seismik (K_g). Hasil penelitian menunjukkan bahwa zona F3-E3 hingga D5 memiliki nilai amplifikasi tinggi, frekuensi dominan rendah, regangan geser meningkat, dan nilai K_g tertinggi. Kondisi ini mengindikasikan lapisan sedimen yang tebal, lunak, kurang terkonsolidasi, serta memiliki kontras impedansi kuat sehingga lebih rentan terhadap guncangan seismik. Interpretasi geologi menunjukkan bahwa zona paling rentan terutama berasosiasi dengan formasi Hulusimpang (Tomh), sedangkan wilayah yang tersusun oleh Kompleks Gunungkasih (Pzg) relatif lebih stabil. Secara umum, zona F3-E3-D5 diklasifikasikan sebagai zona sangat rentan terhadap longsor akibat gempa, zona D3-F4-H3 sebagai zona kerentanan sedang, dan area lainnya sebagai zona risiko relatif rendah.

1. Introduction

Slope instability represents one of the primary geological hazards in regions characterized by steep topography and high tectonic activity. This phenomenon can result in infrastructure damage, loss of life, and socioeconomic disruption, particularly in areas experiencing high rainfall. Consequently, the identification and evaluation of landslide potential constitute critical steps in disaster mitigation and spatial planning, especially in earthquake-prone areas such as Sukorejo Village, Pugung District, Tanggamus Regency. The Tanggamus region lies under the influence of the Semangko Fault Zone, part of the seismically active Sumatran Fault System. Such tectonic activity can amplify local site effects, namely ground motion amplification resulting from shallow geological conditions. Conventional geotechnical approaches such as borehole drilling and laboratory testing present limitations in terms of cost and coverage, necessitating alternative methods that are efficient and non-invasive.

The Horizontal-to-Vertical Spectral Ratio (HVSr) method is a passive geophysical technique that utilizes the ratio between horizontal and vertical components of microtremor signals (Nakamura, 1989). This method yields important parameters including predominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (K_g), which represent subsurface impedance contrast and dynamic soil response to seismic excitation. Various previous studies (Delgado et al., 2000) demonstrate that high amplification values and low frequencies are generally associated with soft soil layers and slope instability potential.

Nevertheless, application of the HVSr method for seismically induced landslide potential analysis in Indonesian hilly regions remains limited, including in Tanggamus Regency which exhibits steep topography and high seismic activity. This study aims to address this gap through application of the HVSr method to evaluate local seismic conditions and their relationship with slope instability potential. The objectives of this study are to:

1. Determine the HVSr parameters, including predominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (K_g);
2. Evaluate the relationship between HVSr parameters and local geological and morphological conditions; and
3. Assess the relationship between seismic amplification and earthquake-triggered landslide susceptibility in the Tanggamus hilly region.

This research is expected to provide a scientific basis for geophysical method-based slope stability analysis, as well as support disaster mitigation strategies in seismically active regions through an accessible, efficient, and non-invasive approach.

2. Data and Methods

This study used primary data collected through single-station microtremor measurements in Sukorejo Village, Pugung District, Tanggamus Regency, Lampung Province, Indonesia. Data acquisition was carried out using a Raspberry Shake seismometer capable of recording three components of ground motion: north-south (N-S), east-west (E-W), and vertical (Z). A total of 37 measurement points were established throughout the survey area, with an average distance of approximately 450 meters between stations (Figure 1).

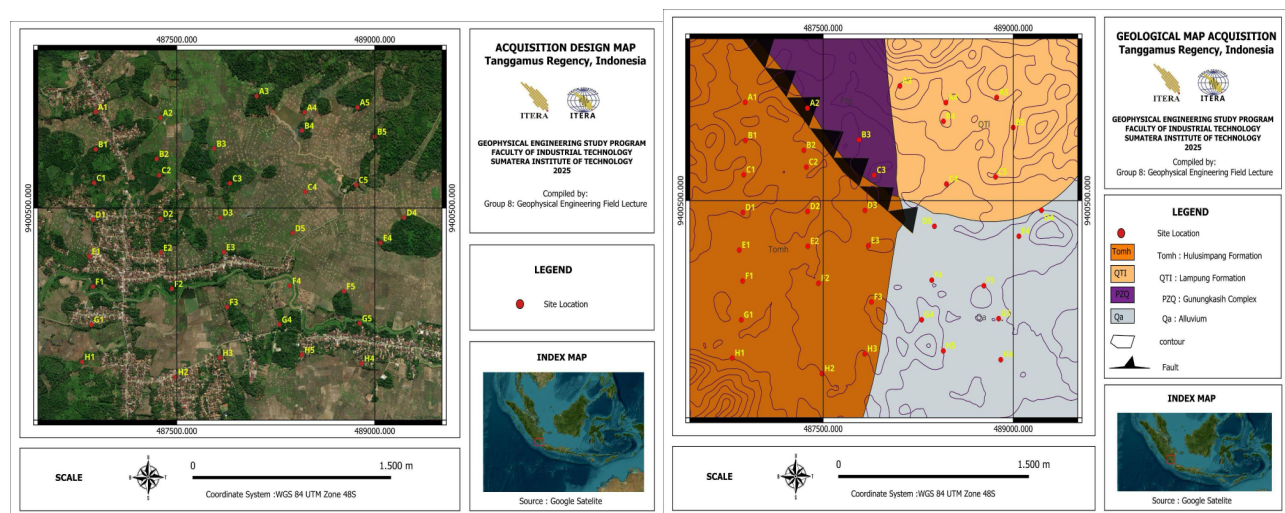


Figure 1. Measurement Location (A) and Geological Research Map (B)

The measurement point locations were selected based on population distribution and human activity, including organizational areas and active agricultural land. Each recording session lasted 30 minutes with a sampling rate of 100 Hz, ensuring signal stability and minimizing anthropogenic interference. The instruments were calibrated prior to use to ensure optimal performance in the field. The geographic coordinates of each point were recorded using a Global Positioning System (GPS) device with an accuracy of approximately ± 3 meters.

The geological map of the research site in Tanggamus Regency shows four main rock units: the Hulusimpang formation (Tomh), the Lampung formation (QT1), the Gunungkasih Complex (PZQ), and alluvial deposits (Qa). The Hulusimpang formation dominates the western and southern parts, consisting of Tertiary-aged volcanic breccia and lava. The Lampung formation is located in the northeast, consisting of tuff and younger volcanic rocks. The Gunungkasih Complex in the northwest

consists of older igneous and metamorphic rocks, while the alluvial deposits scattered in the central and eastern parts consist of sand, gravel, and clay in the plains.

In addition to the rock units, this map displays fault structures indicated by jagged black lines, indicating the influence of tectonics on lithological variations and subsurface conditions. Topographic contour lines are also shown to indicate elevation differences, which aid in determining measurement points and correcting field data. This study consists of several stages, beginning with a literature review, followed by data acquisition, and subsequently data processing using the HVSR method.

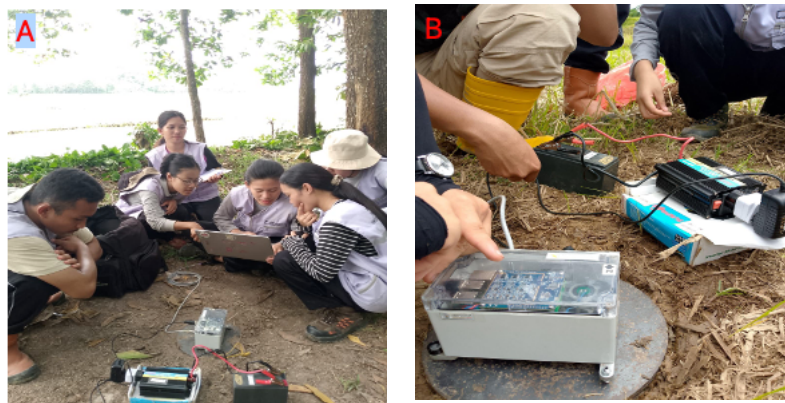


Figure 2. Data Collection Process (A) and Tools Used (B)

This research was conducted directly in the field using a Raspberry Shake tool by recording three components, namely two horizontal components and one vertical component. Next, the data processing was carried out using Visual Studio Code, ProHVSR, Surfer 13 and QGIS applications. Raw data were processed based on SESAME (2004) by ensuring that the points met the criteria and the data could be used properly. After that, the data was processed to obtain A_0 , f_0 , K_g , V_{s30} and GSS values as well as slope gradients and made into an interpolation map.

2.1 Basic Principles of the HVSR Method

HVSR microtremor processing produced a set of microzonation maps for the Tanggamus study area, including amplification factor (A_0), predominant frequency (f_0), seismic vulnerability index (K_g), V_{s30} , ground shear strain (GSS), and slope-gradient maps. These parameters were integrated to evaluate spatial variations in slope-instability potential.

The Horizontal-to-Vertical Spectral Ratio (HVSR) method was first introduced by Nogoshi and Igarashi (1971), who found that the ratio between horizontal and vertical ground motion components was related to the Rayleigh wave ellipticity curve. This concept was further developed by Nakamura

(1989; 2000), who concluded that the horizontal to vertical spectral ratio (H/V) as a function of frequency can be used as an approximation to describe the site transfer function of S-waves. The HVSR method equation, or Nakamura method (Nakamura, 1989), is based on the ratio of the amplitude spectra of the horizontal and vertical components of the microtremor signal. This ratio is expressed as:

$$HHVSR(f) = \sqrt{\frac{[Hx^2(f) + Hy^2(f)]}{V(f)}}$$

where Hx and Hy are the horizontal components, while V is the vertical component at frequency f. The peak of the HVSR curve indicates the dominant frequency (f_0), which represents the resonance of the sediment layer, while the maximum amplitude reflects the amplification factor (A_0).

Predominant frequency (f_0) reflects the resonance characteristics of near-surface layers. Low f_0 values generally indicate thicker sedimentary deposits and a longer natural period, which can increase vulnerability during earthquake shaking. The soil classification based on Kanai predominant frequency is summarized in Table 1.

Table 1. Soil classification based on Kanai predominant frequency

Zone	Dominant frequency (Hz)	Classification
I	< 2.5	Sediment thickness > 30 m
II	2.5-4	Sediment thickness 10-30 m
III	4-10	Sediment thickness 5-10 m
IV	10-20	Sediment thickness < 5 m

In terms of amplification factor values, the higher the amplification factor, the lower the wave velocity. The lower the density of a rock, the higher its amplification factor value will be. Wave velocity decreases due to soft sediments. The amplification values in an area can be classified as shown in Table 2.

Table 2. Classification of amplification factor values

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

Based on the A_0 and f_0 parameters, the seismic vulnerability index (Kg) is calculated using the equation:

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

High K_g values indicate stronger amplification potential and greater susceptibility to seismic excitation. The obtained K_g values were then classified to determine the seismic vulnerability level at each measurement point. The classification criteria used in this study are shown in Table 3.

Table 3. Classification of seismic vulnerability index values

Zone	K_g value
Low	< 3
Medium	3-6
High	> 6

V_{s30} is the time-averaged shear-wave velocity to a depth of 30 m and is widely used to classify near-surface soil conditions and evaluate seismic amplification potential. Low V_{s30} values indicate softer materials that tend to amplify ground motion. V_{s30} is calculated as:

$$V_{s30} = \frac{30}{\sum_{i=1}^n \frac{h_i}{v_{s_i}}}$$

where h_i is the thickness of the i -th layer and v_{s_i} is the shear-wave velocity of that layer.

Peak Ground Acceleration (PGA) represents the maximum ground acceleration at a site and is influenced by earthquake magnitude, hypocentral distance, predominant period, and local site conditions. In this study, PGA was estimated using the Kanai empirical approach:

$$a_{max} = \frac{5}{\sqrt{T_0}} 10^{(0,61M - (1,66 + \frac{3,6}{R})\log R + (0,167 - \frac{1,83}{R}))}$$

The earthquake input used in this analysis was the 1933 Sukabumi earthquake (M 7.52; depth 20 km), obtained from the USGS catalogue. PGA values were then combined with K_g to estimate ground shear strain (GSS). Ground shear strain describes the distortion of a soil element during shaking and is expressed as:

$$\gamma = \left(\frac{A_0^2}{f_0}\right) \times \left(\frac{a_g}{\pi^2 v_b}\right) \times 60\%$$

$$\gamma = K_g (10^{-6}) \times a_g$$

where gamma is ground shear strain, K_g is the seismic vulnerability index, and a_g is the maximum bedrock acceleration in gal. The relationship between strain values and dynamic soil behavior is summarized in Table 4.

Table 4. Relationship between strain values and dynamic soil properties (Nakamura, 1997)

Strain value (gamma)	10^{-6} - 10^{-5}	10^{-4} - 10^{-3}	10^{-2} - 10^{-1}
Phenomenon	Waves, vibrations	Cracks, land subsidence	Landslide, subsidence, soil liquefaction
Dynamic properties	Elastic	Elastic plastic	Collapse; repetition effect; speed effect of settlement

To strengthen the interpretation, the results of this analysis were then correlated with the morphological conditions of the study area using slope gradient classification. This classification refers to the Guidelines for Land Rehabilitation Patterns and Soil Conservation (1986) as shown in Table 5. Through this grouping, the seismic vulnerability level obtained from HVSr parameters can be associated with local geomorphological conditions, thus providing a more comprehensive overview of potential hazards that may occur in areas ranging from flat, gentle, to very steep slopes.

Table 5. Slope classification based on the Guidelines for Land Rehabilitation Patterns and Soil Conservation

Slope (degrees)	Classification
0-8	Flat
8-15	Gently sloping
15-25	Moderately steep
25-45	Steep
> 45	Very steep

3. Results and Discussion

3.1 Results

The amplification factor map (Figure 3) shows the variation in seismic wave amplification values across the study area. High A_0 values (>12) are concentrated in zones F3-E3 to D5. This indicates that seismic waves experience significant amplification as they propagate through shallow soil layers in these zones. This condition is generally associated with the presence of soft, unconsolidated soil material with a high impedance contrast to the bedrock. Conversely, zones A1-A5 and B1-B5 exhibit low to moderate A_0 values, indicating relatively more compact and stable soil conditions.

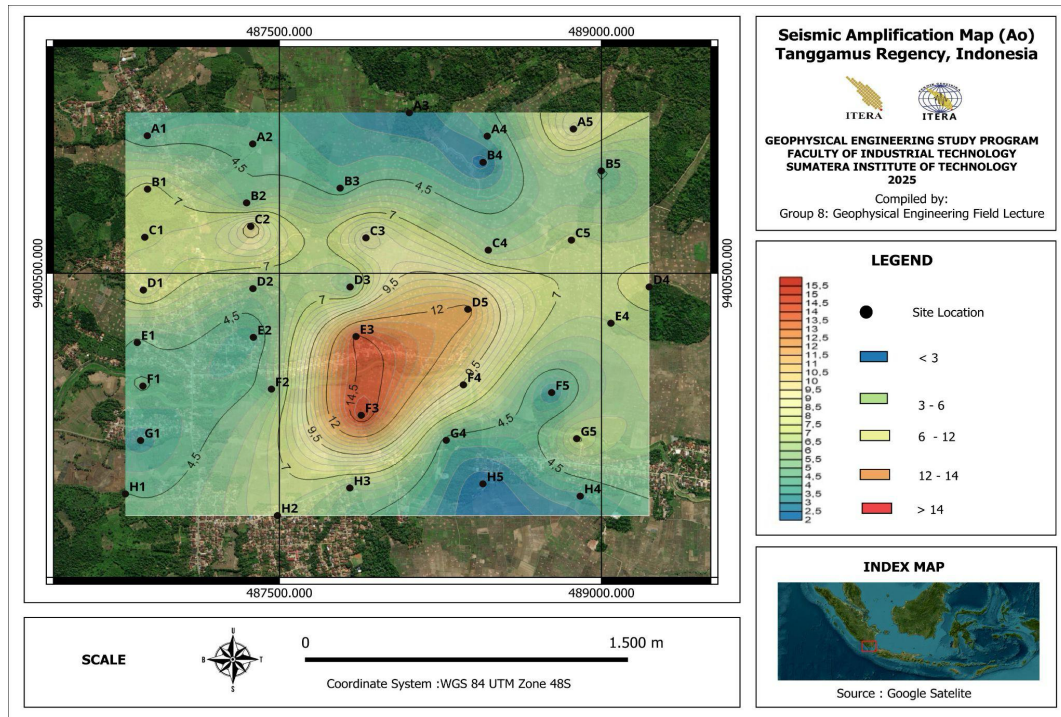


Figure 3. Natural Amplification (A_0) interpolation map

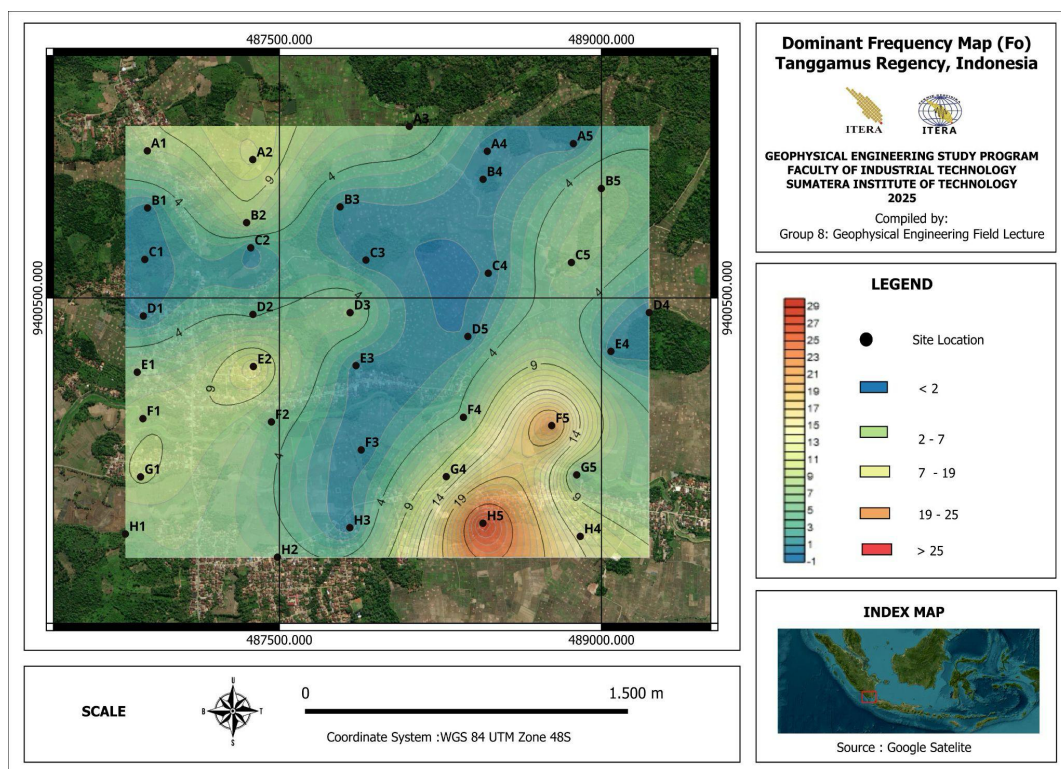


Figure 4. Dominant Frequency (f_0) interpolation map

The dominant frequency map (Figure 4) shows the distribution of f_0 values ranging from 2 to more than 10 Hz. Zones F3-E3-D5 are dominated by low frequencies (2–8 Hz), indicating the presence of a thick sedimentary layer. Low dominant frequencies indicate that the soil layer has a long natural period and has the potential to resonate with long-period earthquake waves, especially on long slopes and

inter-hill valleys. Zones with higher f_0 values (>10 Hz) are generally located in areas with harder rocks and thin sediments.

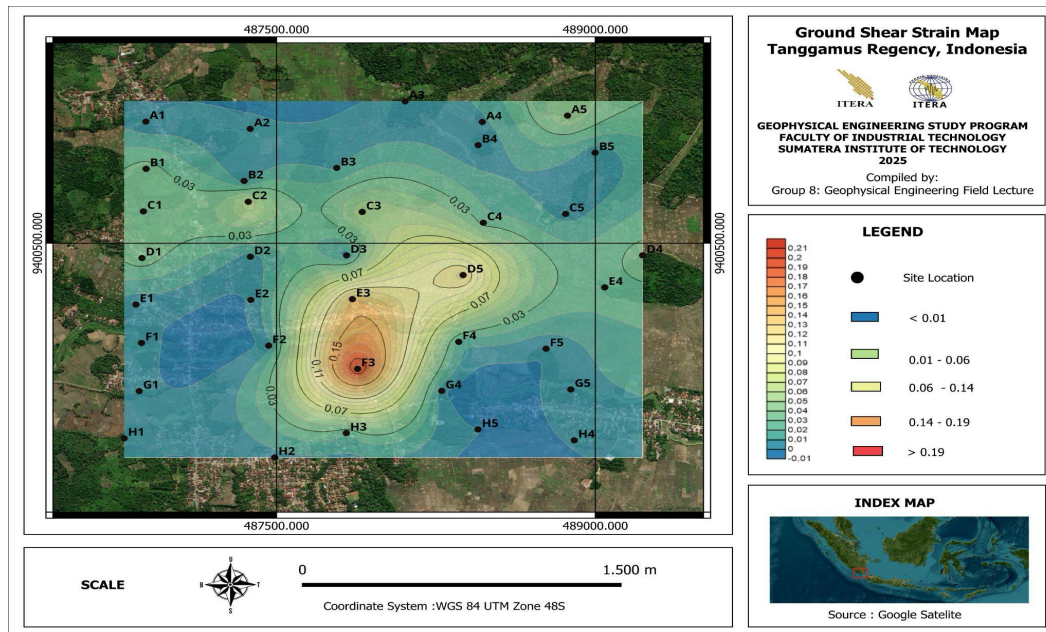


Figure 5. Ground Shear Strain (GSS) map

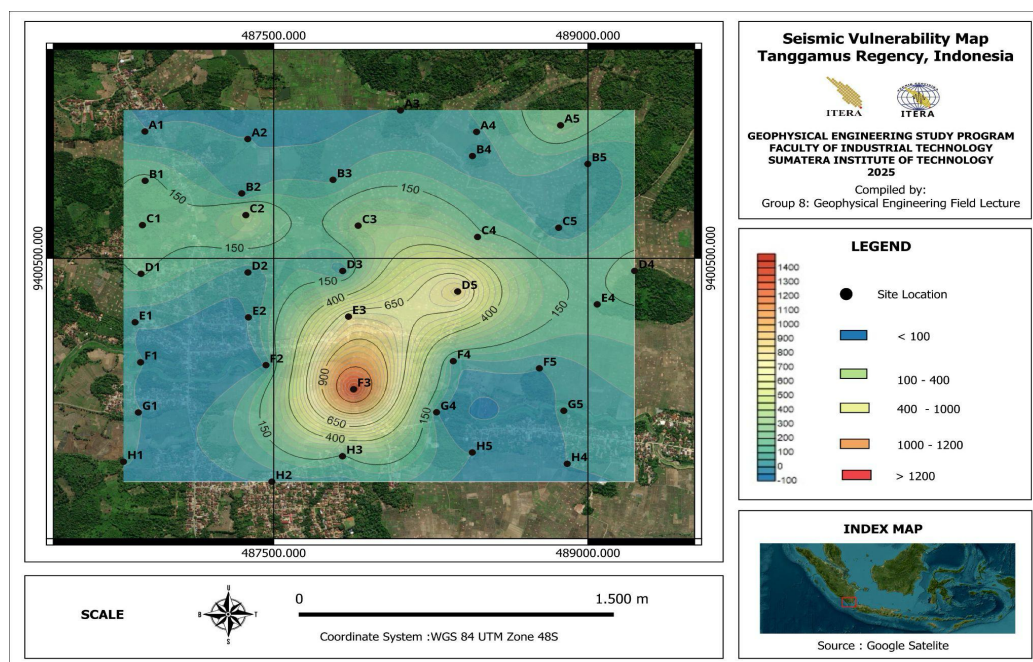


Figure 6. Seismic Vulnerability Index (Kg) map

The soil shear strain map (Figure 5) shows the extent of soil deformation due to seismic shaking. High GSS values (>0.15) are primarily concentrated in zones F3-E3 and parts of D5. This value indicates that the soil in these areas is prone to non-elastic deformation during earthquakes. This condition is often associated with water-saturated, clay-rich

The Seismic Vulnerability Index (Kg) map shows the varying levels of soil vulnerability to earthquake shaking in the study area. Very high Kg values (>1200) are concentrated in zones F3-E3 to D5, indicating a combination of strong seismic wave amplification and low dominant frequencies. This condition reflects the presence of thick, soft sediments that are highly responsive to earthquake shaking, increasing the potential for slope instability. Zones with moderate Kg values are found in the D3-F4-H3 region, indicating a moderate seismic response and moderate landslide potential. Meanwhile, zones A1-A5 and B1-B5 have low Kg values, indicating more stable soil conditions and a lower risk of earthquake-induced landslides. Geologically, zones with high Kg are associated with the Hulusimpang formation (Tomh), while zones with low Kg are found in the Gunungkasih Complex (Pzg).

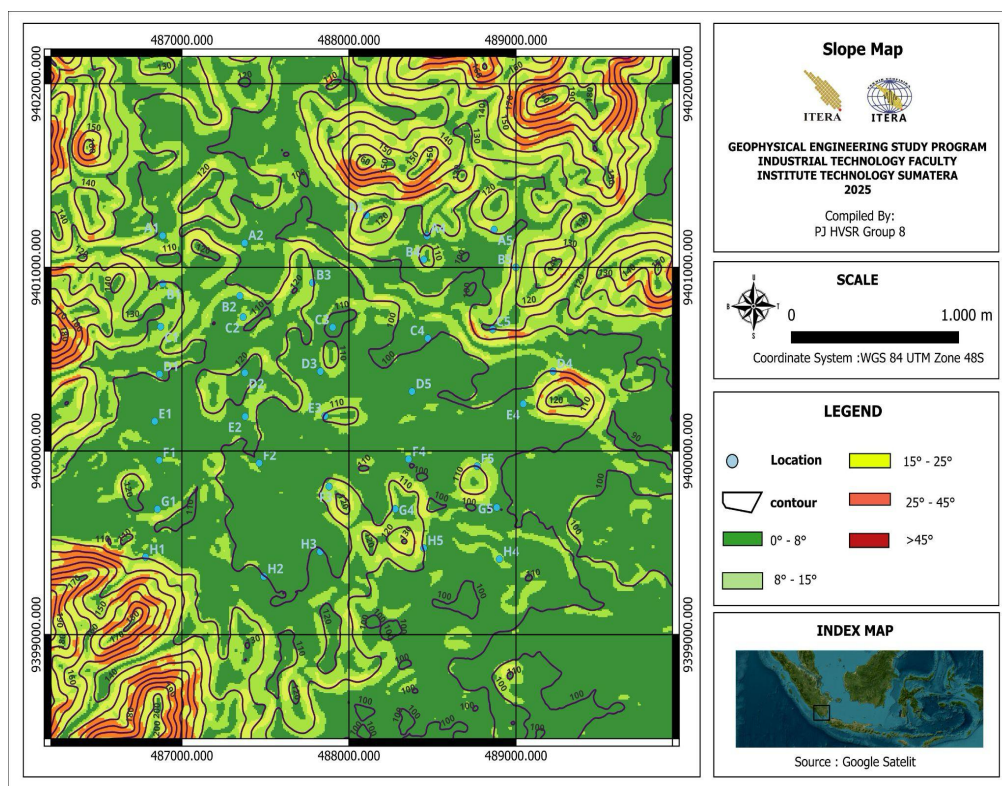


Figure 7. Slope map interpretation

The slope gradient map shows that the study area exhibits quite complex morphological variations, ranging from relatively flat areas to steep slopes. Zones F3-E3 to D5 are dominated by moderate to steep slopes ($\pm 15^{\circ}$ – 45°), which, from a soil mechanical perspective, play a significant role in increasing the driving force on the soil mass. On slopes with steep gradients, the component of the gravitational force parallel to the slope plane increases, making slope stability more sensitive to external disturbances, including earthquake shaking. When an earthquake occurs, ground acceleration, amplified by subsurface conditions, increases the dynamic load on the slope. In zones with moderate to steep gradients, this additional load can significantly reduce the slope's safety factor. Therefore,

although slope gradient is not the sole factor controlling landslides, its presence significantly determines the level of instability when combined with soft soil and high seismic wave amplification. Conversely, zones A1-A5 and B1-B5 are dominated by gentle to moderately steep slopes, resulting in relatively small driving forces. In this condition, even if seismic shocks occur, the possibility of landslides is lower because the stability of the slope can still be maintained by the shear strength of the soil and rocks that make it up.

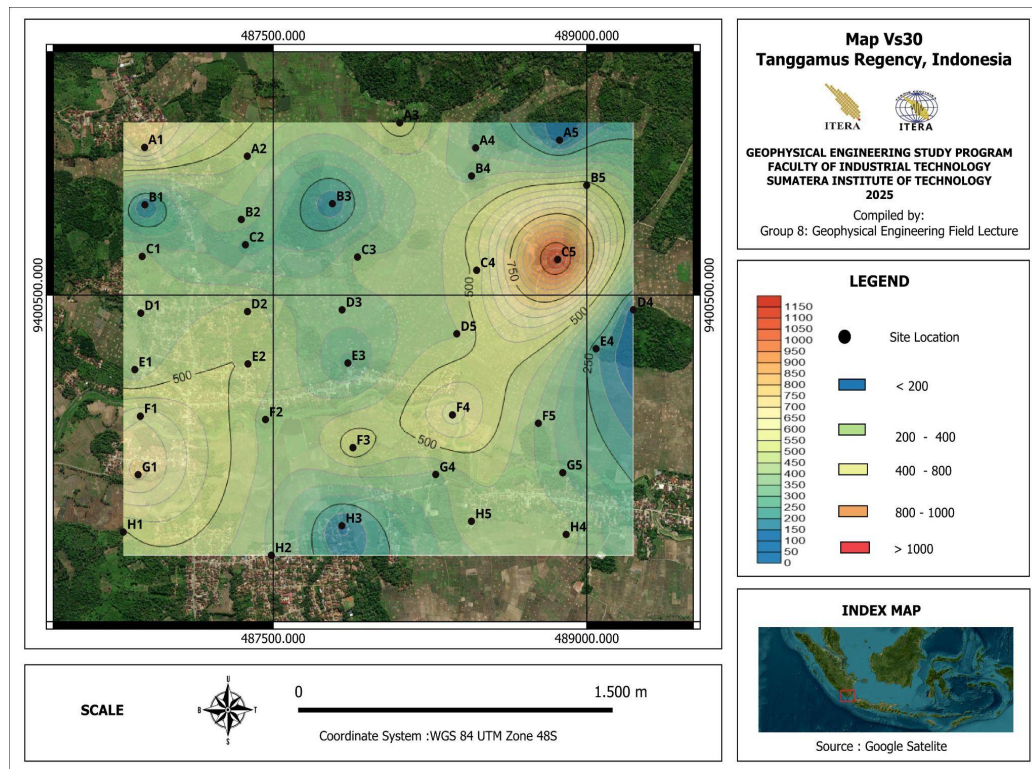


Figure 8. Vs30 map

Vs30 represents the average shear-wave velocity to a depth of 30 m and is used as an indicator of near-surface stiffness. The Vs30 map shows low values in zones F3-E3 to D5, indicating soft soil and thick, poorly consolidated sediment layers. Such materials tend to amplify seismic vibration and deform more strongly during earthquakes, especially where water saturation reduces effective shear strength. Consequently, these zones are more susceptible to displacement and landslides on moderate to steep slopes. In contrast, higher Vs30 values occur in areas associated with the Gunungkasih Complex (Pzg), where compact rock materials reduce amplification and help maintain slope stability.

3.2 Discussion

Based on the mapping results, Ground Shear Strain (GSS), Vs30, slope gradient, and geological maps, slope instability in the study area is influenced by the dynamic response of the soil to seismic shocks

and local morphological conditions. Integration of all resulting maps reveals zones with varying levels of vulnerability to earthquake-induced landslides.

The amplification factor (A_0) map shows high to very high values in zones F3-E3-D5, indicating seismic wave amplification in shallow soil layers. This zone is also characterized by low dominant frequency (f_0) values, indicating the presence of relatively thick layers of sediment and weathered volcanic material. Based on the geological map, these conditions are associated with the Hulusimpang formation (Tomh) and alluvial deposits (Qa), which are composed of loose and poorly compacted material.

High Ground Shear Strain (GSS) values in the same zones indicate significant shear deformation when the soil is subjected to dynamic loads. This indicates a decrease in the mechanical strength of the soil, which can trigger land mass movement. The high seismic vulnerability index (K_g) in zones F3-E3-D5 confirms that this area has the highest seismic response compared to other zones.

The Vs30 map results show that zones with high A_0 , GSS, and K_g have low Vs30 values, indicating soft soils with low stiffness and high seismic response. This condition is exacerbated by the moderate to steep slopes in these zones, which increase the driving forces on the slopes. Conversely, zones with high Vs30 and low K_g , which are generally associated with the Gunungkasih Complex (Pzg), indicate relatively stable slope conditions.

4. Conclusions

This study identified the dynamic soil response and slope-instability potential of Sukorejo Village using HVSR-derived parameters integrated with GSS, Vs30, slope gradient, and geological information. Zones F3-E3-D5 show the highest seismic response, characterized by high A_0 , low f_0 , high K_g , elevated GSS, and low Vs30. These parameters indicate soft, thick, and easily deformed materials that are more susceptible to earthquake-triggered slope failure. The instability potential is further strengthened by moderate to steep slopes and geological units dominated by the Hulusimpang formation (Tomh) and alluvial deposits (Qa). In contrast, zones A1-A5 and B1-B5 show more stable conditions. The results provide an initial basis for earthquake-induced landslide mitigation in the study area, although future work should integrate geotechnical testing, rainfall data, and slope monitoring to obtain a more comprehensive stability assessment.

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