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Landslide Vulnerability Analysis Based on the Seismic Vulnerability Index Using the HVSR Microtremor Method on Cliff Areas in Hanura Village, Teluk Pandan District, Pesawaran Regency

Ikah Ning Prasetiowati Permanasari[1*], Indi Nurazizah Ba'asyir[1], Muhamad Ragil Setiawan[1], Indra Pardede[1], Yeli Monica [1]

[1] *Department of Physics, Faculty of Science, Institut Teknologi Sumatera, Lampung, Indonesia*

Corresponding Authors E-mail: ikahning@fi.ac.id

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Abstract

Way Ratai Road in Pesawaran Regency connects tourist areas managed by the Lampung Provincial Government. This road has cliffs with steep slopes, which have the potential to cause landslides. This research is very important because Way Ratai road is the only access road to Pesawaran beach tourism which is the main tourist destination of Lampung Province. Moreover, Way Ratai road is also the only access road connecting to the provincial capital of Bandar Lampung. This research was conducted to determine the soil vulnerability to seismic vibration on two cliffs around Way Ratai Road, Teluk Pandan District, Pesawaran Regency. The method used was microtremor signal recording with the Horizontal Vertical to Spectral Ratio (HVSR) method to determine the amplification factor (A_0), dominant frequency (f_0), sediment thickness (H), and seismic vulnerability index (Kg). The first cliff's measurement and data processing results showed an amplification factor (A_0) value of 2.74 - 3.70, a dominant frequency (f_0) of 3.75 - 4.56 Hz, a sediment thickness (H) of 14.09 m, and a seismic vulnerability index (Kg) of 2.39 m^2/s. On the second cliff, the results showed an amplification factor (A_0) value of 2.27 - 3.40, a dominant frequency (f_0) of 3.54 - 7.20 Hz, a sediment thickness (H) of 9.33 m, and a seismic vulnerability index (Kg) of 1.84 m^2/s. In term of seismic vibration, both cliffs, prone to landslides, have high stability against seismic vibrations. In the event of a landslide on these two cliffs, the estimated slip surface on the first cliff would be translational, and the second cliff would be a combination of translational and slight rotational, with an estimated volume of soil that could potentially slide on the first cliff is 30,492.16 m^3 and on the second cliff, it is 27,188.92 m^3.

Introduction

Indonesia's geological formation results from the convergence of three major tectonic plates, namely the Indo-Australian, Eurasian, and Pacific. This tectonic activity makes Indonesia a region of high seismicity [1]. The island of Sumatra exemplifies this seismic activity due to the collision between the Indo-Australian and Eurasian plates, which have different densities and create a subduction zone. Consequently, Sumatra is highly vulnerable to natural disasters, including earthquakes that can potentially trigger landslides [2].

Landslides can occur when water infiltrates into layers of soil, thereby reducing friction between hard soil layers and causing the overlying sediment layer to slide down the slope [3],[4],[5],[6],[7]. Seismic activity can worsen this problem by vibrating the ground and destabilizing slopes. Earthquakes cause ground motion that can escalate the balance of soil especially when the soil has already been saturated with water. This effect is more in tropical areas like Pesawaran Regency, where frequent rainfall increases soil saturation and contributes to slope instability. In 2023, there were 334 recorded landslides, with nine occurring in Pesawaran Regency, Lampung Province. This area is known to be prone to landslides, especially around Way Ratai Road. Way Ratai Road is the main access route to tourist destinations in Lampung Province which passes through cliffs that are prone to landslides. The tourism sector in Pesawaran Regency is very important for Lampung's economy because the main attraction for tourists to Lampung is beach tourism, most of which are located in Pesawaran Regency with access via Way Ratai Road. If a landslide occurs along Way Ratai Road, it will cut off access to these tourist attractions and cut off access for local people to the capital of Bandar Lampung Province. This has an economic impact, including a decrease in regional income [8].

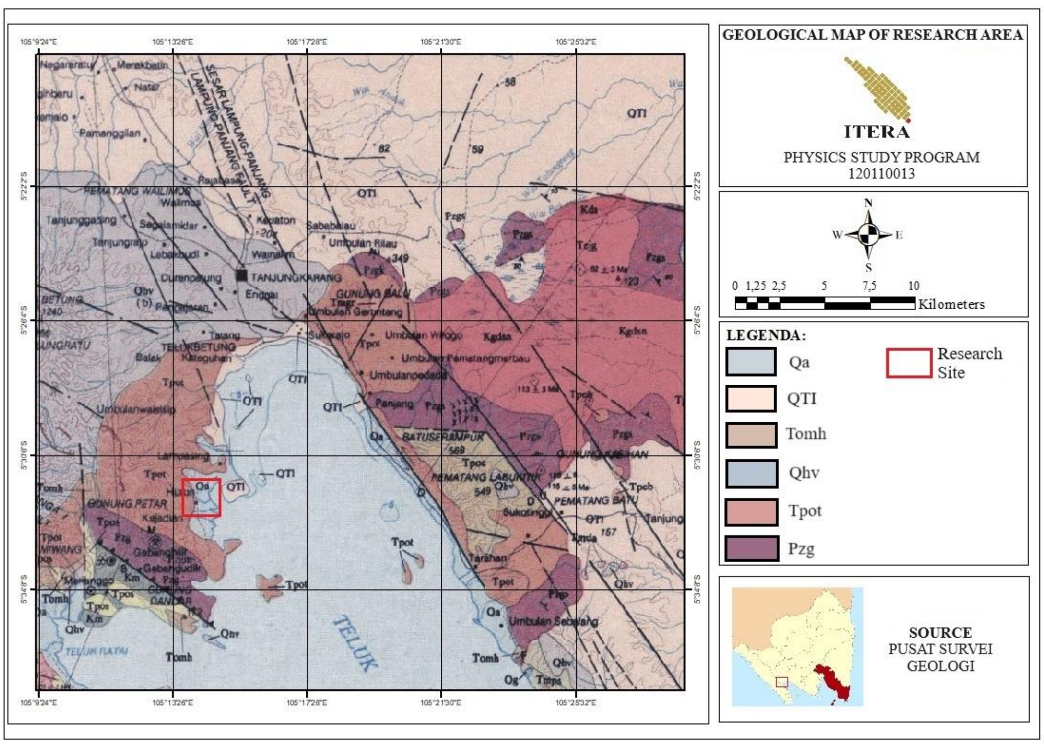

Figure 1. Geological map of research area [15]

The geological conditions of the research are shown in Figure 1. Three rock groups represent the geological conditions of the research area: the pre-tertiary, tertiary, and quaternary rock groups. The pre-tertiary rock group consists of schist, quartzite, and gneiss. The tertiary rock group includes tuff, sandstone, breccia, and andesite-basalt lava. Meanwhile, the quaternary rocks consist of clastic volcanic deposits such as gravel, sand, silt, and tuff. Pesawaran Regency has an average monthly rainfall intensity of 152.58 mm and an average of 12.1 rainy days per month. Around Way Ratai Road, Pesawaran Regency is classified as a landslide-prone area with fairly steep slopes, reaching more than 40%[9][10][11][12].

This research aims to be conducted on soil vulnerability on the cliffs around Way Ratai Road on two cliffs in Hanura Village, Teluk Pandan District, Pesawaran Regency, Lampung Province, with coordinates – 5.54175 S, 105.24110 E and – 5.54453 S, 105.24220 E. This study uses the HVSR method that records microtremor vibration data on Earth's surface [13][14][15]. Passive seismic methods have been widely adopted in the past two and a half decades, especially in the context of landslide investigations associated with seismic hazard analysis and co-seismic triggering mechanisms [16]. The microtremor vibration data are processed using the Horizontal to Vertical Spectral Ratio (HVSR) method to determine two important parameters are amplification factor and dominant frequency [9][17][18][19]. These parameters are then used to obtain sediment thickness and seismic vulnerability index, which can explain soil vulnerability from the seismic aspect that may cause landslides. This technique has thus been widely employed to examine diverse types of landslide occurrences[20][21][22][23]. This research is important because a landslide in the study area could block road access [24][25]. The geophysical method used in this study is the HVSR method using microtremor vibration data recordings on the earth's surface. The use of this method is very simple and does not require significant costs.

Theory and Calculation

A. Landslides

Landslides are the movement of soil or rock moving downward or away from a cliff due to a disruption in soil stability. The main cause of landslides is the presence of water mixed with material, increasing the soil load. Landslides are primarily caused by the presence of water mixed with soil and other materials, which increases the overall load and reduces slope stability. They can also be triggered by seismic vibrations, such as those generated by earthquakes, which disrupt the balance of forces acting on the slope. Seismic activity may reduce the frictional strength between soil layers, elevate pore water pressure, and alter load distribution. Landslide occurrence is governed by the interaction between driving and resisting forces acting on the slope. Driving forces are influenced by factors such as slope angle, soil load, and soil type, whereas resisting forces are primarily determined by the density and cohesion of the soil [26][27].

B. Dominant Frequency

Dominant frequency is the natural frequency of the layer in the study area that can explain the thickness of sediment layers. If the dominant frequency value in the study area decreases, then the soil in the study area will become more vulnerable to seismic vibrations due to the thickness of the sediment layers[29]. The characteristics of the soil and rock types in the study area can be indicated by their dominant frequency values. A classification table of dominant frequency values can be seen in Table 1

Table 1. Classification of soil types based on dominant frequency values [28]

Type	Dominant Frequency (f_0)	Information
Type IV	6.67 - 20	Tertiary or older rocks, includes sandstone and gravel tops
Type III	4 – 6.67	Alluvial rock include sand gravel, hard clay, and clay
Type II	2.5 - 4	Alluvial rocks include sand gravel, hard clay, clay, and siltstone
Type I	f_0 < 2.5	Alluvial rocks are formed form delta sediment, top soil, and clay

C. Sediment Thickness

Sediment thickness indicates layers of soil that have undergone weathering and deposition on top of the bedrock[29]. The sediment thickness value can determine the volume of soil experiencing collapse by involving the dominant frequency value and shear wave velocity at a depth of 30 meters. This information can be used to calculate the sediment thickness value presented in Equation (1) [30].

$$H = \frac{V_S(30)}{4f_0} \tag{1}$$

$V_S(30)$ is the shear wave speed at a depth of 30 meters (m/s)

D. Seismic Vulnerability Index

The soil's susceptibility to seismic vibrations depends on the soil and rock conditions in the study area. The seismic vulnerability index can be used for landslide mitigation, particularly for preparedness against seismic vibrations, as it indicates the level of susceptibility of soil layers that may result in deformation. First, we obtained the amplification factor and the dominant frequency values, then the seismic vulnerability index was calculated using Equation (2) [30][31].

$$Kg = \frac{(A_0)^2}{f_0} \tag{2}$$

Where, Kg is the index seismic vulnerability (m^2.s). The values of the seismic vulnerability index can be classified into several groups as shown in the table below.

Table 2. Classification of seismic vulnerability index [20]

Classification	seismic vulnerability index (Kg)
Low	Kg < 3
Currently	3 ≤ Kg < 6
High	6 ≤ Kg < 9
Very high	Kg > 9

Method

The measurement of microtremor signals was conducted at two landslide-prone cliffs, namely T01 and T02. Each cliff has three measurement points: T01-1, T01-2, T01-3, T02-1, T02-2, and T02-3. Seismic signals were recorded using seismographs placed at each measurement point. Measurements were taken for 60 minutes at each point, with a distance of approximately 100 meters between each point. The data obtained from these measurements are used to analyze landslide potential and soil vibration characteristics. The research design, including the location and configuration of the measurement points, is shown in Figure 2. Microtremor signal measurements were conducted on two cliffs, with each cliff having three measurement points. These three points form a trapezoidal spatial structure, which was adapted to the condition of the cliffs. By forming this spatial structure, it becomes possible to estimate the volume of potential landslides should one occur.

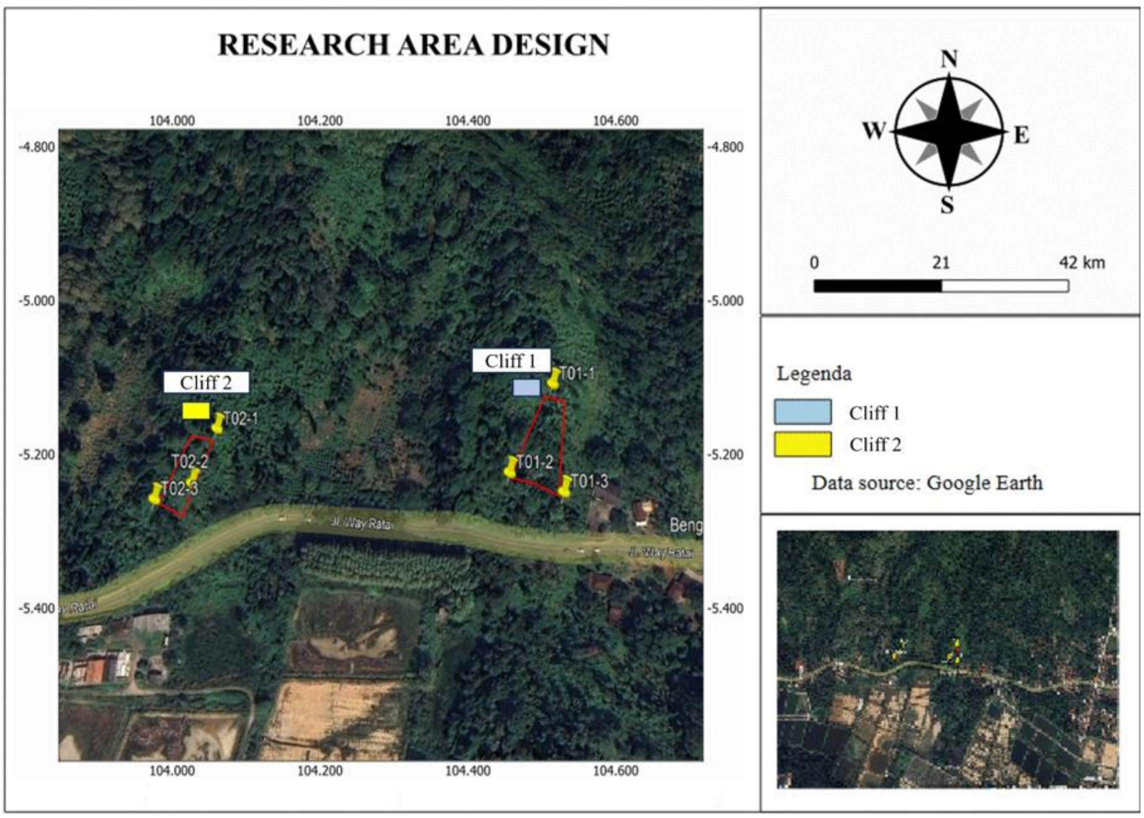

Figure 2. Research area design

The data used in this study is primary data obtained from microtremor measurements using the HVSR method to determine the natural frequency and soil amplification on the cliffs around Way Ratai Road, Hanura Village, Teluk Pandan District, Pesawaran Regency, Lampung Province. Horizontal to Vertical Spectral Ratio (HVSR) method to compare horizontal and vertical signal components [17]. The microtremor waves used are obtained from the conditions of the study area, such as sea winds, traffic activity, and conditions that describe the area. The H/V curve results show amplification factor values (A_0) and dominant frequencies (f_0). These two parameters are important to prevent resonance processes. If the dominant frequency value in the geological study area matches the dominant frequency of a landslide structure, resonance and amplification processes will occur [17][20][28].

Table 3. Numerical Classification of amplification factor values

Classification	Amplification Factor (A_0)
Low	$A_0 < 3$
Currently	$3 \leq A_0 < 6$
High	$6 \leq A_0 < 9$
Very high	$A_0 > 9$

The measurement points are located at coordinates -5.54175 S - 105.2411 E and -5.54453 S - 105.2422 E. The microtremor measurements were conducted by placing a seismometer at the measurement points, which recorded seismic wave vibrations on the ground surface. The data obtained from these measurements were then processed using the Geopsy software for data picking, resulting in the values of amplification factor and dominant frequency. The data obtained from Geopsy was subsequently compiled using Microsoft Excel and used to create maps with Surfer software.

Result and Discussion

Result

The results of the microtremor vibration recordings processed using the HVSR method with Geopsy software produce an H/V curve (see Fig. 3). From the H/V curve, amplification factor values and dominant frequency are obtained to get value sediment thickness, seismic vulnerability index, estimated land volume to be landslide, and estimated slip plane shape can be calculated.

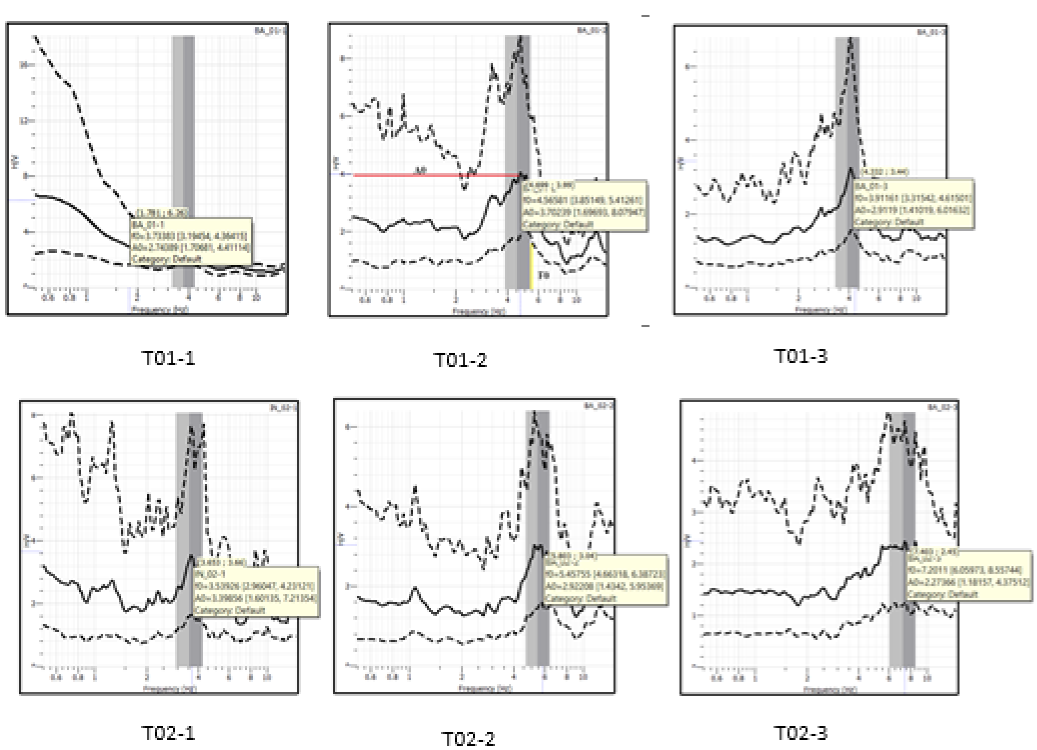

Figure 3. HVSR curve from cliff one and two

The values for seismic vulnerability index dominant frequency, sediment thickness, and amplification factor, for cliffs one and two can be seen in Table 4 and Table 5.

Table. 4. Amplification factor values, dominant frequency, sediment thickness, and cliff one seismic vulnerability index.

Point	Lat	Long	A_0	f_0	H	Kg
T01-1	−5.54194	105.2406	2.74	3.73	12.86	2.01
T01-2	−5.54166	105.2411	2.70	4.56	14.25	3. 00
T01-3	−5.54175	105.2411	2.91	3.91	15.18	2.16

Table. 5. Amplification factor values, dominant frequency, sediment thickness, and cliff two seismic vulnerability index.

Point	Lat	Long	A_0	f_0	H	Kg
T01-1	−5.54416	105.2414	3.40	3.54	15.25	3.26
T01-2	−5.54416	105.2419	2.92	5.45	9.07	1.56
T01-3	−5.54453	105.2422	2.27	7.20	3.67	0.71

Based on Table 5, the classification of seismic vulnerability index values on the slope shows that point T02-1 has the highest seismic vulnerability index of 3.26 m^2.s, with a moderate classification, which indicates that this point has low stability when seismic vibrations increase. The dominant frequency value of 3.54 Hz suggests that the soil and rock at point T02-1 consist of soft soil, such as alluvial soil and rock, including sand, gravel, clay, and silt, with a sediment thickness of 15.25 m. Additionally, the high amplification factor value indicates that point T02-1 has the potential for significant damage due to the soil and rock's softness and the sediment layer's thickness. Seismic vibrations passing through point T02-1 may be amplified, resulting in a fairly high level of damage.

In contrast, point T02-3 has the lowest seismic vulnerability index of 0.71 m^2.s, with a low classification, which indicates that point T02-3 has high stability when seismic vibrations pass through it. The dominant frequency value of 7.20 Hz indicates that the soil and rock at point T02-3 consist of hard soil, such as tertiary soil and rock, including sandstone, with a sediment thickness of 3.67 m. The low amplification factor value indicates that point T02-3 has a low potential for damage. The thin sediment layer and the hard characteristics of the soil and rock mean that seismic vibrations passing through point T02-3 will have a low level of amplification.

The value of the seismic vulnerability index describes the susceptibility of the ground surface to seismic vibrations. The distribution map of the seismic vulnerability index for slope one can be seen in Figure 4.

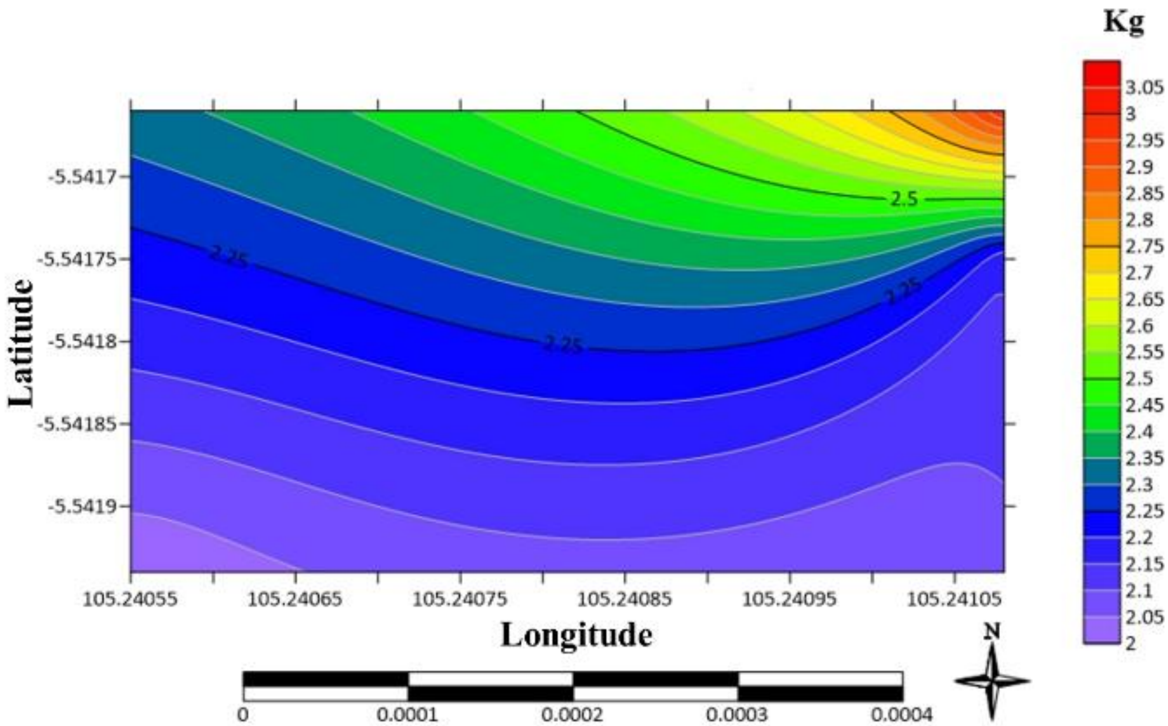

Figure 4. Map of the distribution of cliff one seismic vulnerability index values

The map shows that the color gradient from purple to orange indicates that the area is lowly vulnerable to seismic vibrations, with values ranging from 2.00 to 2.95 m^2.s. In contrast, red indicates a moderate vulnerability to seismic vibrations, with values ranging from 3.00 to 3.05 m^2.s. The distribution map of the seismic vulnerability index for slope two is shown in Fig. 5.

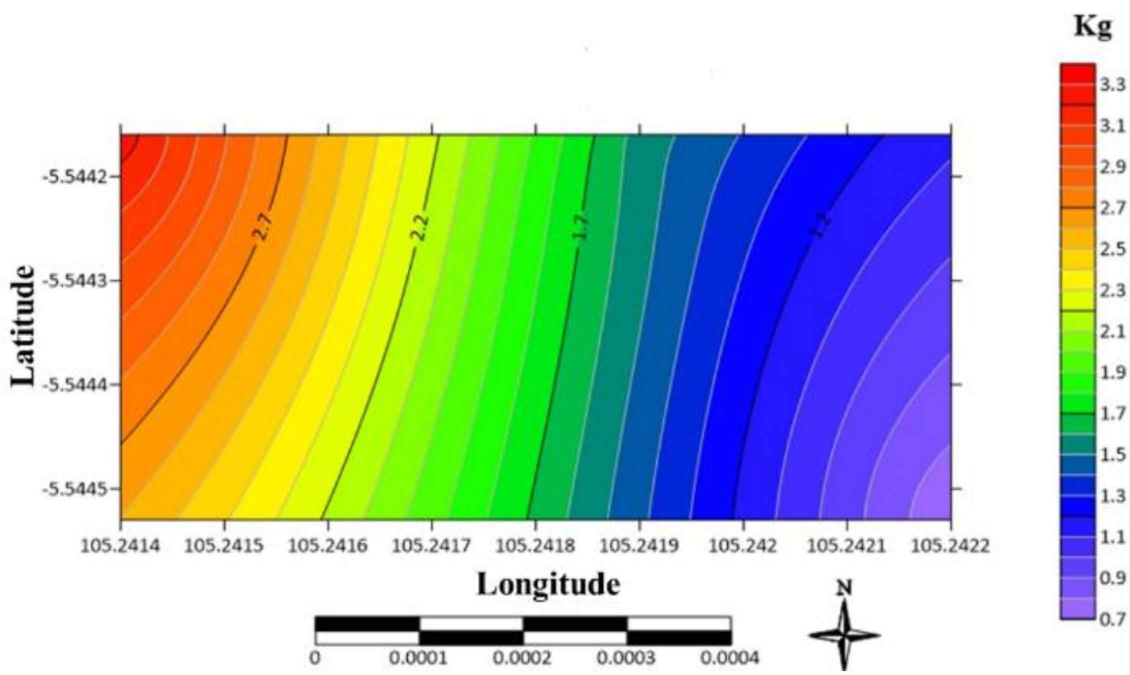

Figure 5. Map of the distribution of cliff two seismic vulnerability index values

The seismic vulnerability index distribution map on slope two shows that the colors from purple to orange indicate low vulnerability to seismic vibrations with values between 0.7 and 2.9 m^2.s. Colors ranging from pink to dark red indicate moderate vulnerability to seismic vibrations with values between 3.1 and 3.3 m^2.s

The data processing results indicate that the seismic vulnerability index in the study area can describe the land's vulnerability to deformation caused by seismic vibrations. Seismic vibrations passing through soft soil layers can produce high-period vibrations, leading to ground movement and potential landslides. According to Table 3, one cliff point, T01-2, has the highest seismic vulnerability index of 3.00 m^2.s with a moderate classification, indicating low stability when exposed to seismic vibrations. The dominant frequency value of 4.56 Hz reflects the characteristics of the soil and rock types at point T01-2, which consist of alluvial soil and rock such as gravelly sand, hard clay, and clay with a sediment thickness of 14.25 m. The high amplification factor value indicates significant potential damage due to the thickness of the sediment layer in the area. Seismic vibrations passing through sediment layers can be amplified, resulting in greater damage. Point T01-1 has the lowest seismic vulnerability index of 2.01 m^2/s with a low classification, indicating high stability when seismic vibrations pass through this point. The dominant frequency value of 3.73 Hz reflects the type of soil and rock at point T01-1, which consists of alluvial soil and rocks such as sand, gravel, hard rock, and clay, with a sediment thickness reaching 12.86 m. The low amplification factor value indicates a low potential for damage due to the thin sediment layer. Therefore, if seismic vibrations pass through this point, the amplification level will be low.

Discussion

Based on the microtremor signal recordings and data processing using the HVSR method at three measurement points on each of the landslide-prone research cliffs, the results are as follows: Cliff one has a seismic vulnerability index ranging from 3.75 to 4.56 Hz, while cliff two has a seismic vulnerability index ranging from 3.54 to 7.20 Hz. The potential for landslides due to seismic vibrations in the research area is relatively low. However, since both cliffs have slopes greater than 40% and are categorized as very steep, with sediment thicknesses of 14.09 m and 9.33 m, respectively, both cliffs are at risk of landslides. The cause of landslides on these cliffs is not earthquakes but other factors, such as high rainfall, improper land construction, inappropriate deforestation, etc. If a landslide occurs on either cliff, the estimated shape of the slip surface on cliff one can be seen in Figure 6. The estimated landslide volume within the study area was calculated using a geometric solid approach. In this research, the shapes of both slope one and slope two were approximated as irregular trapezoids. The parameters used to compute the landslide volume include the surface areas of the upper and lower bases, the height of the study area, and the sediment thickness. The estimated geometry of the slip surface on both landslide-prone slopes was derived based on sediment thickness and the topographic characteristics of the slopes.

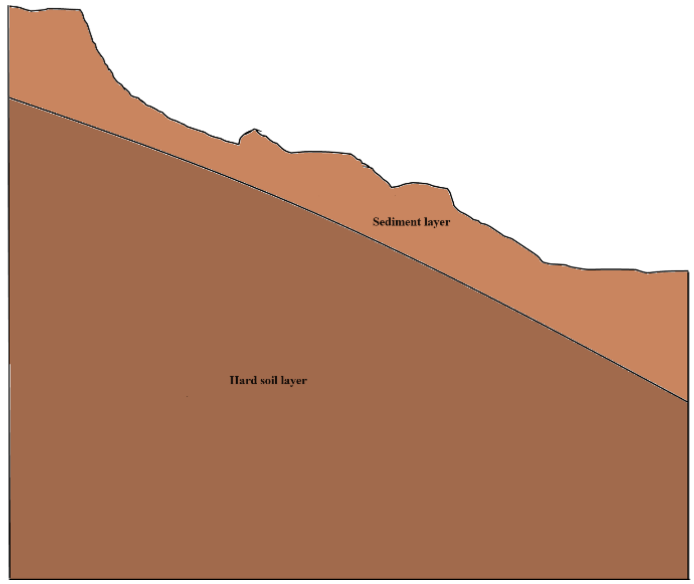

Figure 6. Approximate shape of cliff slip plane one

An illustration of the estimated slip surface shape on slope one is presented in Figure 6. Light brown indicates sediment layers, while dark brown represents hard soil layers. The estimated slip surface shape of the slope is horizontal or translational. The estimated volume of soil collapse on slope one is 30,492.16 m³.

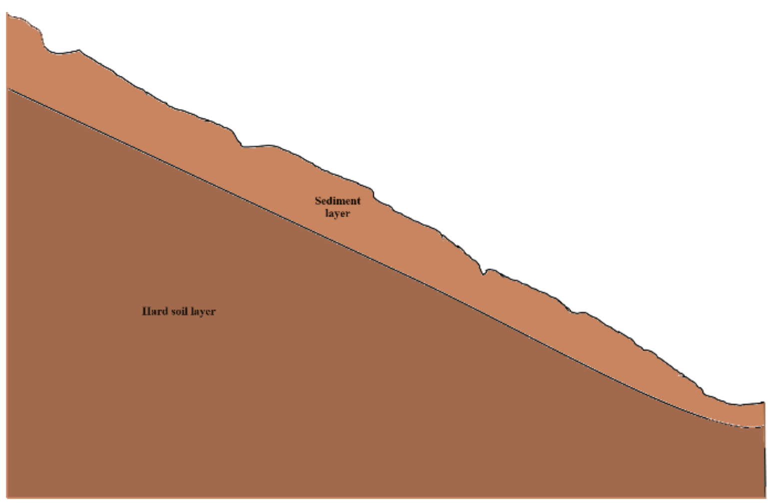

Figure 7. Approximate shape of cliff slip plane two

An illustration of the estimated shapes of the two cliff slip areas is presented in Figure 7. Light brown indicates sediment layers, while dark brown indicates hard soil layers. The shapes of the two cliff slip areas are estimated to be a combination of horizontal and somewhat concave. The estimated soil volume likely to collapse on Cliff Two is 27,188.92 m³.

Mitigation efforts that can be undertaken include the installation of retaining walls, as well as the planting of shrubs that function both as ground cover and rainwater absorbers. Importantly, activities involving cut and fill at the slope toe, which acts as a critical support for the slope's resisting forces, should be strictly avoided, as this practice can significantly reduce the risk of landslides.

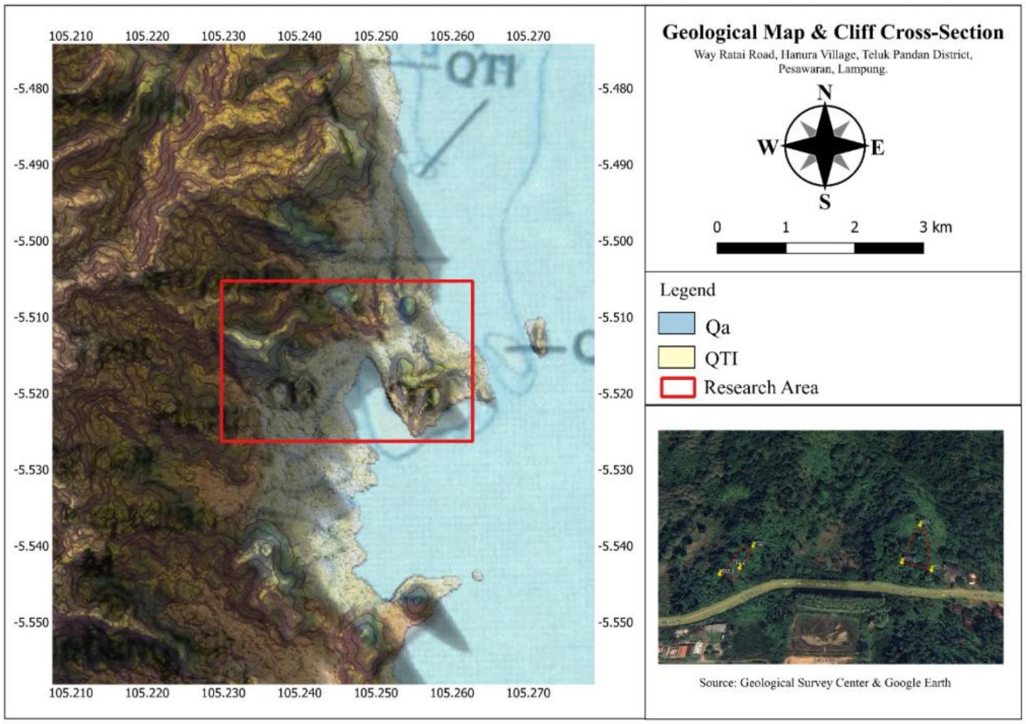

Figure 8. Geological Map and Cliff Cross Section

Figure 8 shows an overlay of the geological map of the study area with the illustration of the slip surfaces presented in Figures 6 and 7. It can be observed that the dominant material in the study area, as indicated by the results, is consistent with the geological map, which shows that the area is predominantly composed of alluvial deposits. The color differences indicate the location of the bedrock, which in this context can serve as a reference for identifying the position of the slip surface.

Conclusion

From the data processing results, concluded that the amplification factor for Cliff One ranges from 2.74 to 3.70, while for Cliff Two, it ranges from 2.27 to 3.40. The dominant frequency value for cliff one is between 3.75 and 4.56 Hz, whereas for cliff two, it ranges from 3.54 to 7.20 Hz. The sediment thickness at Cliff One reaches 14.09 m, while at Cliff Two, it is 9.33 m. The seismic vulnerability index for Cliff One is 2.39 m^2.s, while for Cliff Two, it is 1.84 m^2.s. Additionally, it is estimated that the slip surface shape for Cliff One is translational, whereas for Cliff Two, it is a combination of translational and rotational.

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