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Micro-Zonation Mapping of Landslide Potential Using Statistical Weighting Method of Analytical Hierarchy Process (AHP) in South Bengkulu–Lahat Road for Disaster Mitigation

Arif Ismul Hadi[1]*, Budi Harlianto[1], Nurul Hudayat[2], M. Farid[1], Frinsyah Virgo[3], Darmawan Ikhlas Fadli[1], Fadillah Humairah[1]

[1] Department of Geophysics, the University of Bengkulu, Kandang Limun, Bengkulu, Indonesia.
[2] National Research and Innovation Agency, Jl. M.H. Thamrin, Jakarta, Indonesia.
[3] Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Jl. Raya Palembang-Prabumulih, Palembang, Indonesia.

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Corresponding Author:
Arif Ismul Hadi
ismulhadi@unib.ac.id

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Abstract: The research objective was to identify areas with high, medium, and low potential for landslides by micro-zonation on the South Bengkulu–Lahat road, map areas with potential for landslides based on the parameters that contribute to causing landslides using the AHP method, and determine the parameters for landslides, the dominant parameter affecting the occurrence of landslides in the study area. To achieve the research objectives, all parameters that cause landslides obtained at measurement points are then overlaid using the AHP statistical weighting method. The results showed that the area along the South Bengkulu–Lahat road had been identified microzoning high, medium, and low landslide potentials based on statistical weighting from parameters were obtained at the measurement points. For areas with high landslide potential, caution should be exercised, especially during the rainy season with high intensity and long duration.

Keywords: AHP; Landslide; Micro-zonation; Overlaid; South Bengkulu–Lahat road

Introduction

The geographical location of the South Bengkulu area, Bengkulu province, Indonesia is near the source of the earthquake, both from the ocean in the form of a subduction zone (movement of the Indo-Australian tectonic plate) and from the mainland in the form of the Manna segment of Sumatran fault (Petersen et al., 2004; Megawati et al., 2005; PUSGEN, 2017; Hadi, 2019). The movement of the Indo-Australian tectonic plate has the greatest tectonic energy and strain rate around the Bengkulu province, including South Bengkulu regency. The implication is that it can trigger faults and high seismic activity in this area compared to other areas on the island of Sumatra (Murjaya, 2011; Megawati et al., 2005; PUSGEN, 2017). In addition, the presence of the Manna segment of the Sumatran fault that crosses the South Bengkulu regency (Natawidjaya et al., 2007) makes this area prone to earthquakes originating from the mainland. If an earthquake occurs on a slope, it can trigger landslides. Areas adjacent to earthquake sources are areas that have a higher potential for triggering landslides than other areas (Hadi, 2015; Hadi et al., 2018; Hadi, 2019; Hadi et al., 2021b).

Rainfall in South Bengkulu regency is quite high, between 2553 – 4771 mm/year (data for 2017 to 2021) (BMKG, 2022) or an average of 4248 mm/year (data for 2021) (BPS, 2021). The amount of rainfall is due to Bengkulu province, including South Bengkulu regency, which is an inter-tropical convergence zone (ITCZ) area

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where rainfall is high throughout the year (Sudradjat, 2007). If the rainfall is > 2500 mm/year, it has a great potential to cause landslides (Kirmanto, 2007). Based on its elevation, the plains of South Bengkulu regency which has a height above 100 m above sea level is 49.12% (BPS, 2021). The elevation area is related to the slope of an area, the steeper the slope, the easier it is to experience landslides. Areas with slopes above 35° are areas with high landslide potential (Zuidam, 1983; Kirmanto, 2007).

One area that has a topography with a steep slope is the South Bengkulu–Lahat road. This road is an access for the people of South Bengkulu regency to Lahat regency, South Sumatra. Based on the slope map overlaid with a regional geological map (the presence of faults), this road has a slightly steep to very steep slope. In addition to being located near the Sumatran fault in the Manna segment, this road is also traversed by secondary faults that can trigger land earthquakes and land movements that cause landslides.

Based on the above conditions, South Bengkulu regency especially the South Bengkulu – Lahat road, has a high potential for landslides. However, the potential for landslides is not solely determined by the parameters above, but there are several other parameters that can affect the occurrence of landslides. The other parameters include ground shear strain (GSS), peak ground acceleration (PGA), geological parameters in the form of average shear wave velocity to a depth of 30 m (V_{s30}), and weathering levels, rock condition (Hadi et al., 2021b). All parameters that can contribute to landslides need to be thoroughly correlated, so that the factors causing landslides can be identified in the study area. To correlate all these parameters, the Analytical Hierarchy Process (AHP) statistical weighting method will be used through overlaying the fault distance to the measurement point, rainfall, slope, slope height, rock conditions, GSS, PGA soil surface, and V_{s30}.

The study of landslide potential in the study area is still on a regional scale and uses a different method, namely Simple Additive Weighting (SAW) (BPBD, 2021). For this reason, further research will be studied locally or micro-zonation and use other methods, namely the AHP statistical weighting method, so that the research results will be studied in more depth and detail. The selection of the AHP statistical weighting method to determine the potential for landslides because of its reliability, for example a structured quantitative decision-making process can be documented and replicated, can be applied as decision support for situations involving multi-criteria, can be applied as decision support for situations which involves subjective assessment, uses qualitative and quantitative data, can provide a preference measure of consistency, and is particularly suitable for group decision support (Steiguer et al., 2003). Based on the reliability possessed by the AHP method, the potential for landslides can be mapped by involving all the parameters that contribute to causing the landslide in the study area. The novelty of this research is the integration of parameters that influence landslide occurrences into the AHP method.

This study is very important to do because landslides can cause the cut off-of the South Bengkulu – Lahat cross road access and even fatalities. Through mapping in this research area, it can be seen at which points have high, medium, and low landslide potential by micro-zonation. By knowing the potential for landslides at these points, this research can contribute to disaster mitigation as an effort to reduce disaster risk, especially in the South Bengkulu regency, Bengkulu province.

Method

Data acquisition and collection was carried out to obtain secondary data and primary data in the form of field surveys. Secondary data include the presence of faults around the study site, bedrock PGA, earthquake catalog, slope, rainfall, and Vs30. The existence of these faults can be obtained through regional geological maps of the Manna and Enggano Sheets (Gafoer et al., 2007). Bedrock PGA data were obtained from the national earthquake center or PUSGEN (2017) by entering the coordinates of each research point. Furthermore, earthquake catalog data were obtained from the International Seismological Center (ISC) and the United States Geological Service (USGS) for 100 years from 1921 to 2021. Earthquake catalog data were useful as input to obtain the PGA value of the ground surface through the Kanai method (Douglas, 2022). The slope data was obtained from the topographic map of Indonesia (RBI) South Bengkulu regency with a scale of 1:50000 sourced from the Geospatial Information Agency (BIG) in 2016 with digital elevation model (DEM) analysis and shuttle radar topography mission (SRTM) via ArcGIS Software ver. 10.8.2. The slope map is used as a reference in the field survey. Rainfall data was obtained from the Meteorology, Climatology and Geophysics Agency (BMKG) of Bengkulu province for five years from 2017 to 2021. The Vs30 data was obtained from InaRisk with a grid spacing of 30 m.

A field survey was conducted to obtain microtremor data using the Horizontal to Vertical Spectral Ratio (HVSR) method. Taking the research zoning points on the HVSR method was adjusted to field conditions by taking coordinate points referring to the regional geological maps of the Manna and Enggano Sheets. To determine the coordinate points used the help of Google Earth Software and Global Positioning System

(GPS). From each of the coordinates of the research location, several data points were taken including latitude, longitude, and altitude data. A set of tools used for the HVSR survey are the PASI Gemini-2 Seismometer (triaxial geophone), laptop, digitizer, and power. The output of this HVSR survey is the value of the dominant frequency of the soil and its amplification. In addition, slope and slope height data are also taken at these coordinates. For in-situ slope measurements, the Suunto Level/Clinometer tool is used, while the slope height is measured directly or using a topographic map.

Data acquisition refers to the standard Site Effects Assessment using Ambient Excitation (SESAME). According to SESAME (SESAME, 2004), the length of data collection can give good results if the dominant frequency of the research site is low enough. To obtain representative data, the field data acquisition was taken for 30 minutes for all research locations. The data of the dominant period of the soil and its amplification value along with the PGA value of the bedrock are used as input to obtain the GSS value.

After obtaining secondary data from several related sources and field surveys, the data processing stage was carried out. At the coordinate points of the research location, measurements of the fault distance (epicenter) to the measurement point (epicentral distance) were carried out. Furthermore, the PGA values for bedrock, slope, rainfall, and V_{s30} were plotted according to the coordinates of the research location points together with the field survey data. Earthquake catalog data in the form of latitude and longitude of the epicenter, magnitude, and depth of the earthquake from the seismic records are processed to obtain the PGA value of the ground surface. The data obtained from the USGS and ISC earthquake catalogs are still not uniform in magnitude. For this reason, before further processing, it is necessary to convert it into the same magnitude scale. The magnitude scale that is not yet uniform is converted into a moment magnitude unit (M_w) which is an earthquake magnitude that is consistent in showing the magnitude of the earthquake strength (Hanks and Kanamori 1979). The PGA value of the soil surface can be obtained through the formula from Kanai (Douglas, 2022):

$$\alpha = \frac{5}{\sqrt{T_G}} 10^{0,61M_W - 1,66\log_{10} R - \frac{3,60}{R}\log_{10} R + 0,167 - \frac{1,83}{R}}, \quad (1)$$

where is the peak ground acceleration (gal), R is the closest distance from the location to the earthquake source (km), M_w is the moment magnitude scale, and T_G is the dominant period of the ground measurement point (s).

Microtremor data obtained in the field using the HVSR method is still in the time domain which consists of three components, namely the North South component (N-S), the East West component (E-W), and the Vertical component (U-D). HVSR technique is done by selecting the signal in the windowing. To get the most stationary signal, signal selection is done manually. In the windowing process, the stationary signal is divided into several windows. The determination of the window width refers to the SESAME European Research Project (SESAME, 2004).

After windowing, the conversion transformation is carried out into the frequency domain with Fast Fourier Transform (FFT). After obtaining the FFT results, the two horizontal components are combined, namely the spectrum of the N-S component and the spectrum of the E-W component, so that the ratio of H/V values is obtained, namely the spectrum of the horizontal component and the vertical component. So that the resulting data is good, it is necessary to carry out a data smoothing process. The smoothing process in this study uses the Konno et al. (1998) equation with the selection of available bandwidth. The next data processing is in the form of HVSR curve analysis. The output of the HVSR method is the dominant soil frequency (f_0) and the amplification value (A_0) at the research site. The dominant frequency values of the soil and the amplification used as input parameters to produce the GSS (γ) value at the soil surface are (Nakamura et al., 2003; Nakamura, 2008):

$$\gamma = \left(\frac{A_0^{\,2}}{f_0^{\,2}}\right)\left(\frac{1}{\pi^2 V_b}\right) a_{\max}, \quad (2)$$

where A_0 is the amplification factor, f_0 is the natural frequency (dominant frequency), V_b is the average shear wave velocity in the bedrock (600 m/s), $a_{\max}$ is the bedrock PGA.

The recorded microtremor data obtained in the field were then analyzed for the wave spectrum using Win-MASW 5.2 HVSR software from PASI, Torino, Italy (PASI, 2019). This software is a package program to get the value of the dominant ground frequency and its amplification. In this program, the source of the microtremor from the horizontal component (N-S and E-W) and the vertical component (U-D) can clearly see the difference in the signal between the natural vibration and the transient vibration, making it easier to select the data used for the next process. This program can also determine the reliability of the data and the clear peaks of H/V at each research location.

Location points that have the potential for landslides based on the GSS value are then mapped using ArcGIS software ver. 10.8.2. After obtaining the parameters from the results of the analysis using the HVSR method as well as the slope parameters, slope height, fault distance to the measurement point, rainfall, soil surface PGA, and V_{s30} at the measurement location, then they are thoroughly correlated using the Analytical Hierarchy Process statistical weighting method. (AHP).

Data interpretation is based on contour maps generated from field surveys in the form of GSS values, soil surface PGA, slope and slope height, soil conditions correlated with secondary data in the form of V_{s30} values, fault distance to measurement points, and rainfall. Areas that have GSS values, soil surface PGA, slope and slope height, and high rainfall are areas that have high landslide potential as well. For the value of V_{s30} and the low fault distance to the measurement point is an area with high landslide potential, while the soil condition is related to the level of weathering of the rock. The more weathered a rock, the more prone it will be to landslides or the potential for landslides is high. The correlations of all GSS parameters, PGA ground surface, slope and slope height, soil conditions, V_{s30}, fault distance to measurement point, and rainfall above are then overlaid using the AHP statistical weighting method, so that the potential for landslides from each point can be determined. research sites. The result of this activity is a map of the potential for landslides in the research area locally (micro-zonation). In this landslide potential map, the highest score is an area that has a high landslide potential and vice versa. A brief research flowchart can be seen in Figure 1.

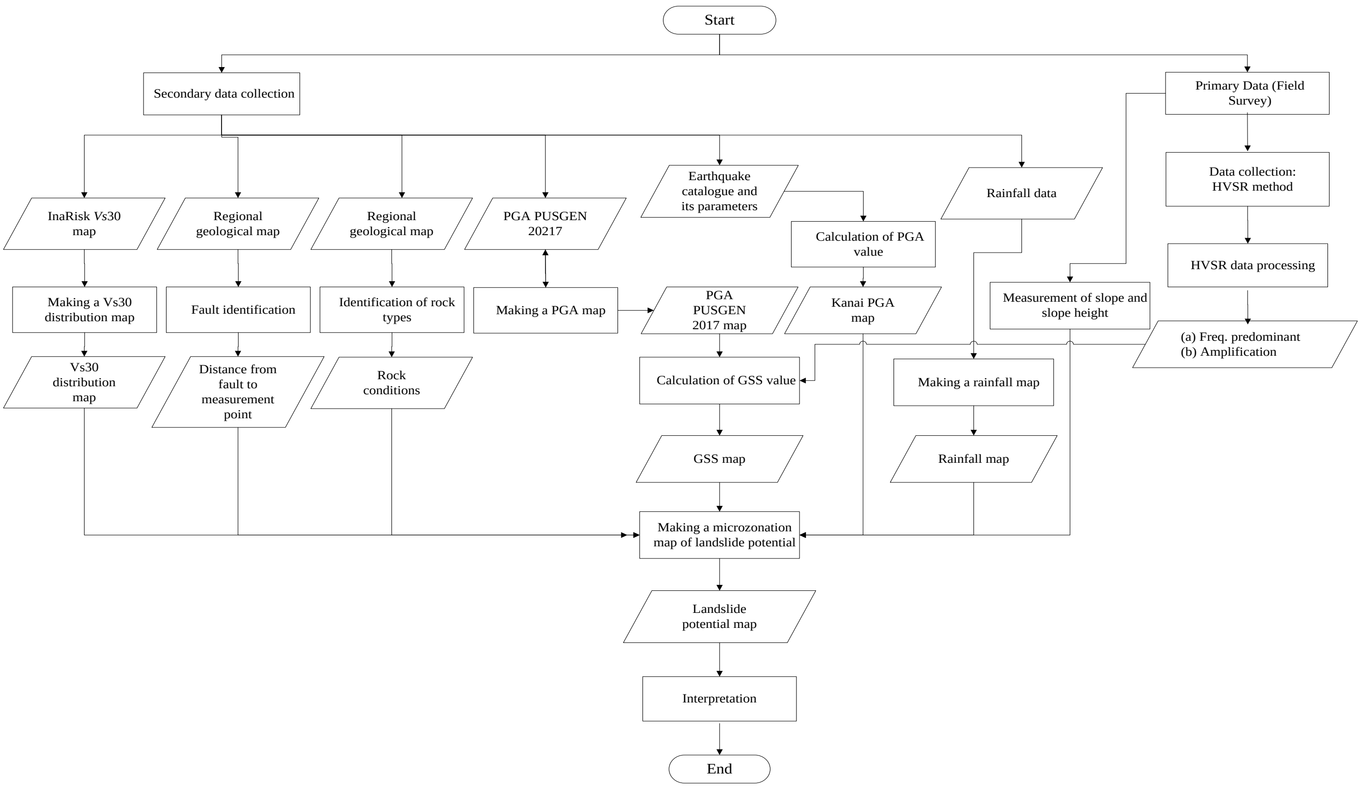

Figure 1. Research flowchart

Result and Discussion

Regional Geology of South Bengkulu

This study has been carried out on the Bengkulu Selatan-Lahat highway. The research location consists of 48 points along the causeway. The research points are scattered in various rock formations. According to the regional geological map, the rock formations along the causeway consist of the Seblat formation (Toms), Lemau formation (Tml), and Simpangaur formation (Tmps) (Amin et al., 1994) as shown in Figure 2.

The Seblat formation is the oldest Tertiary sedimentary rock in the Bengkulu Basin which consists of sedimentary rocks deposited by regression (Heryanto, 2006). The lithology of the Seblat formation in this area is an alternation of claystone, calcareous claystone, siltstone mixed with sandstone and conglomerate. The Lemau formation disproportionately overlapped the Seblat formation. The Lemau formation consists of claystone, coal, sandstone, calcareous claystone, and conglomerate (Yulihanto et al., 1995). Furthermore, the Simpangaur formation unconformably overlaps the Lemau formation which consists of sandstone, conglomerate sandstone, mudstone containing mollusk shells, and tuffaceous rock deposited in the transition area (Gafoer et al., 2007). The lithologies of these rock formations can affect the physical properties of the rock, so that it will also have an impact on the potential for landslides in the study area.

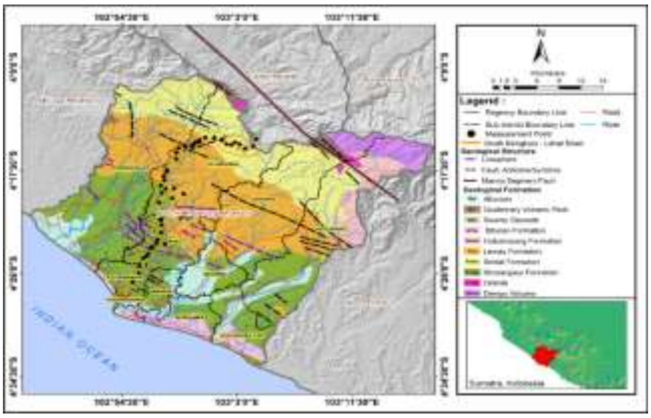

Figure 2. South Bengkulu regional geological map along with the research location points along the South Bengkulu – Lahat road (modified from (Amin et al., 1994))

Rainfall

The annual rainfall in South Bengkulu regency is categorized as quite high, from 2500 mm/year to > 4500 mm/year (Figure 3). Rainfall data was obtained from the Meteorology, Climatology and Geophysics Agency of Bengkulu province between 2015 – 2021 (BMKG, 2022). Based on Figure 2, it appears that the research area along the Bengkulu Selatan – Lahat causeway ranges from 3243 mm/year to > 4649 mm/year. Areas with annual rainfall above 2500 mm/year are areas with high potential for landslides (Kirmanto, 2007; Hadi et al., 2018). Landslides or ground movements triggered by high rainfall can occur due to rainwater infiltration into the slopes which pushes the soil to become landslides due to increased load (Karnawati, 2007).

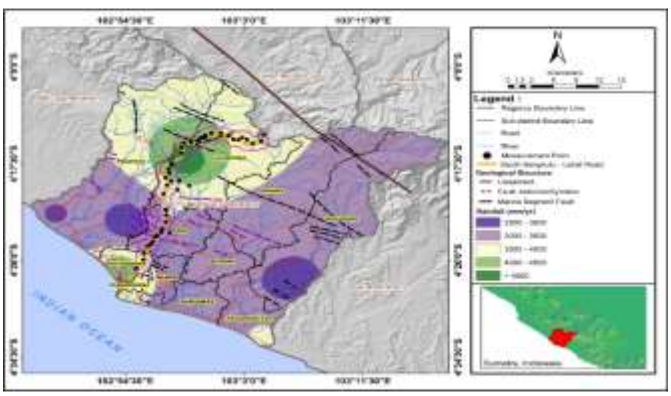

Figure 3. Annual rainfall map in South Bengkulu regency and study location points along the South Bengkulu – Lahat road (modified from (BMKG, 2022))

V_{s30} Research Area

V_{s30} is the average shear wave velocity value up to a depth of 30 m (Bisch et al., 2012; SNI, 2019). V_{s30} is a very useful geotechnical parameter for seismic wave analysis. According to Wangsadinata (2006), only rock layers up to a depth of 30 m determine the magnitude of earthquake waves, so in this study we did not study the average shear wave velocity of more than 30 m. V_{s30} data is obtained from the calculation of average shear wave velocity in the upper 30 m (AV_{S30}) using a topographic class approach from Digital Elevation Model (DEM) raster data (InaRisk BNPB, 2023). The distance between the measurement points of the AV_{S30} data is about 30 m. Based on AV_{S30}, the value of V_{s30} is between 165 m/s to 875 m/s (Figure 4). For locations along the South Bengkulu–Lahat causeway it is 260 m/s to 875 m/s. The greater the speed of the seismic waves, the more solid the rock and vice versa (Capizzi & Martorana, 2014; Hadi et al., 2021a). The nature of rock that is less solid affects the magnitude of the potential for landslides that occur in an area.

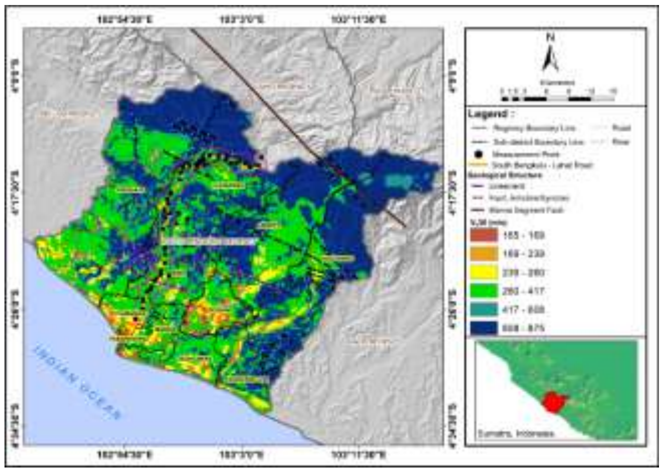

Figure 4. V_{s30} map from the South Bengkulu regency area and the study location points along the South Bengkulu – Lahat road (InaRisk BNPB, 2023)

Slope

The slope is one of the factors that influence the occurrence of landslides. The class division of the slope refers to the classification of the slope from Zuidam (1983). The slope in the South Bengkulu regency area is between 4° - 8° (sloping) to above 55° (extremely) as shown in Figure 5. For the study area along the South Bengkulu–Lahat road, the slope is obtained 4° (sloping) to 37° (very steep). The greater the slope angle, the greater the potential for landslides. In some cases in the field, it shows that slopes of more than 40° have a high potential for landslides (Karnawati, 2007; Hadi et al., 2018; Hadi, 2019).

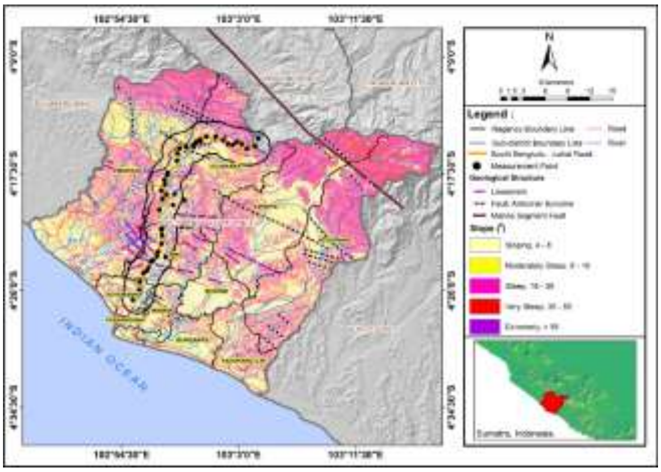

Figure 5. Slopes map of the South Bengkulu regency and the research location points along the South Bengkulu – Lahat road. The slope map is based on the Indonesian Geospatial Map (RBI) from the Geospatial Information Agency (BIG) with a scale of 1:50000

Fault Distance

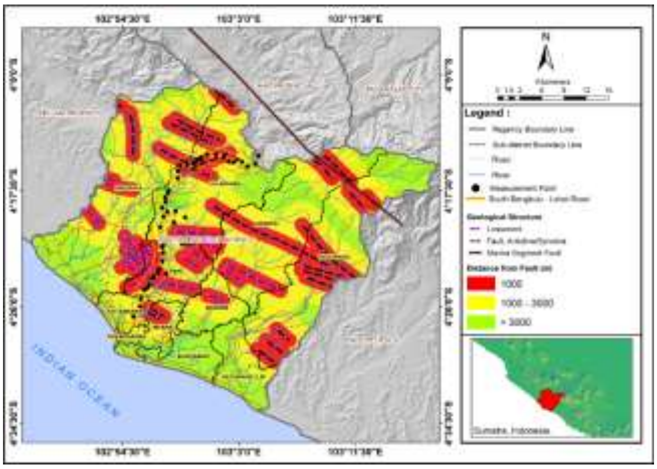

Figure 6. Map of the presence of main and secondary faults in South Bengkulu regency along with the research location points along the Bengkulu Selatan–Lahat road. The existence of faults in the study area was taken from the regional geological map of the Manna and Enggano Sheet with scale 1:250,000 (modified from Amin et al. (1994))

The existence of faults is very influential on the occurrence of landslides in an area. Based on the regional geological map of the Manna and Enggano sheets with a scale of 1:250000, it shows that there are main faults and secondary faults in the area (Figure 6). The main fault in the area is the Sumatran fault, the Manna segment, which is oriented towards the Southeast – Northwest. For secondary faults, the orientation of the direction is relatively the same as the orientation of the main fault. The distance of the fault to the study location is between < 1 km to > 3 km. The closer the fault distance, the greater the landslide occurrence and the level of damage to an infrastructure will be. An example of a case in the field is the earthquake that occurred due to the movement of the Sumatran fault in the Babakan Bogor segment. This earthquake occurred on October 14, 2017 at 12:27:34 UTC with a magnitude 3.7. This earthquake was located at coordinates -3.70° latitude and 102.48° longitude with a depth of 10 km centered at a distance of 2 km southwest of Kepahiang city (BMKG, 2017). This earthquake caused cracks on the highway, cracks in the walls of buildings and houses of residents in Bogor Baru village, Kepahiang sub-district, Kepahiang regency, Bengkulu province. The damaged area is about 263 m from the Babakan Bobor fault line (Hadi, 2019).

Land Cover

Land cover is a manifestation of the presence of vegetation, natural objects, built-up land, and so on which are located above the earth's surface (Syahbana, 2013). Modification of land cover can occur due to changes in forest function for agricultural expansion or due to floods, forest fires, and others (Molders, 2012). For areas that have land cover in the form of forests, lush natural vegetation is an area that has low potential for landslide events (Hamdouni et al., 2022; Masithah et al., 2020). The research area along the South Bengkulu–Lahat road consists mostly of mixed dry agricultural land and the rest is dry land forest and settlements (Figure 7). The residential area is located in the southern part of the study area.

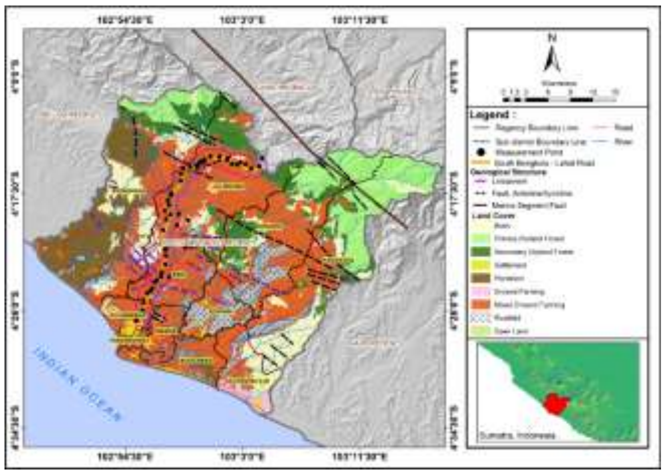

Figure 7. Map of South Bengkulu regency land cover along with the research location points along the South Bengkulu–Lahat road (modified from (KLHK, 2022))

Peak Ground Acceleration (PGA)

The PGA value used in this study is the PGA of the soil surface rock from the Kanai formulation in Equation (1). PGA values obtained in the study area ranged from 0.18 g – 0.77 g (Figure 8). The greater the PGA value in an area, the greater the potential for landslides and vice versa (Hadi et al., 2021c). In this study, the largest PGA values were in the southern, central, and northern regions. The magnitude of the PGA value can be assumed to be influenced by rock conditions related to the value of the dominant period of the soil which is quite large and the thickness of the sediment layer is quite thick.

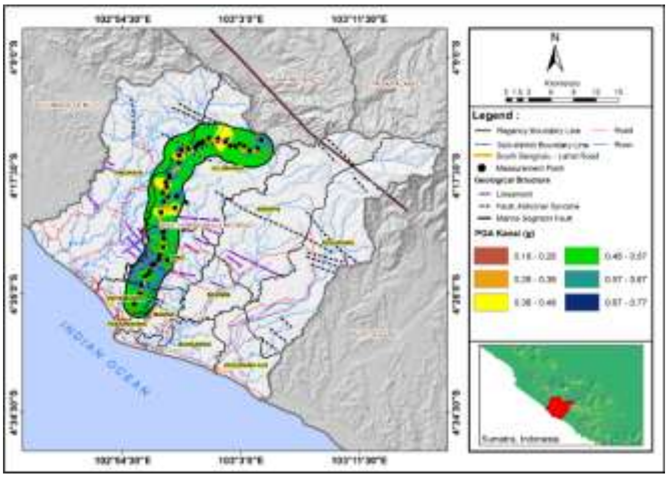

Figure 8. PGA map with Kanai formulation along the South Bengkulu–Lahat road

Ground Shear Strain (GSS)

The GSS value is obtained from Equation (2). In this study, the GSS values obtained ranged in the order of 10^{-4} to 10^{-3} (Figure 9). The greater the GSS value, the more easily the rock will stretch and result in a high potential for landslides. The magnitude of this GSS value indicates that these areas have a high vulnerability to landslide potential (Hadi, 2019). The magnitude of the GSS value is also influenced by the seismic vulnerability index and PGA. The greater the seismic vulnerability index and PGA, the greater the GSS. For calculating the GSS value, bedrock PGA input from PUSGEN (2017) is used. The PGA value of bedrock in South Bengkulu regency is between 0.44 g to 0.61 g (PUSGEN, 2017).

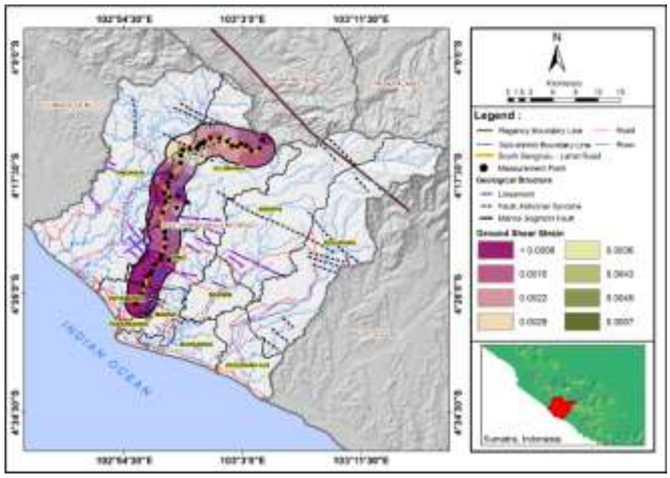

Figure 9. GSS map with kanai formulation along the South Bengkulu – Lahat road

Microtremor Data

To obtain microtremor data, the HVSR method was used. Microtremor data obtained in the field as many as 48 measurement points. Based on the reliability analysis, the 48 microtremor data met the reliability requirements of SESAME (SESAME, 2004). This shows that the quality of the data used is good and can be scientifically justified. An example of microtremor data obtained in the field is shown in Figure 10. Furthermore, based on the value of the dominant frequency (f_0) and amplification (A_0) obtained in the field, then it is used to calculate the GSS (Equation 2).

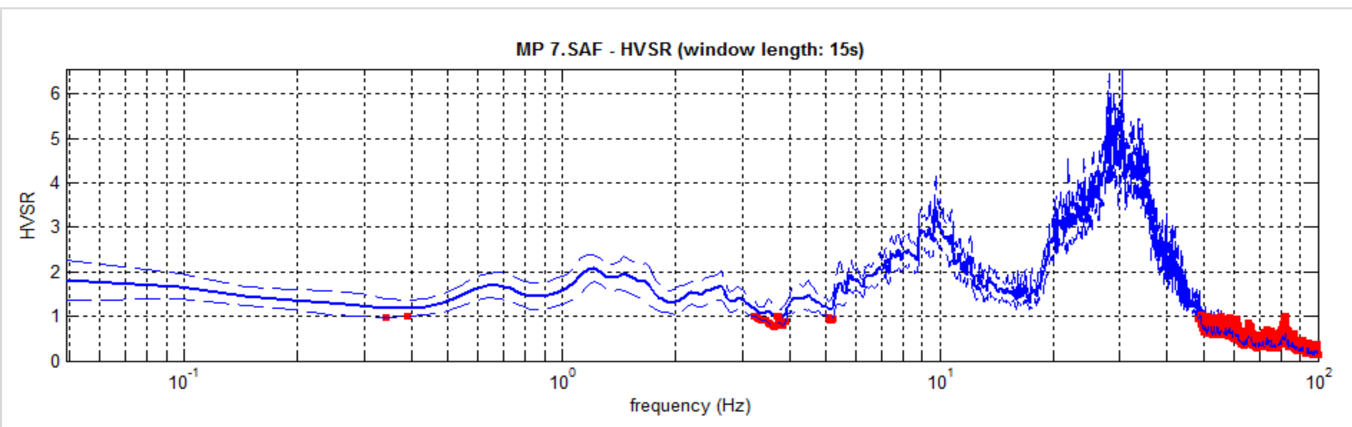

Figure 10. Example of microtremor data with f_0 = 9.8 (±3.4) and A_0 = 3.5 (±0.6) at the MP7 measurement point with window length = 15 s and sampling frequency = 200 Hz

Landslide Potential Map

After the parameters of rainfall, slope, GSS, soil surface PGA, V_{s30}, the distance from the measurement point to the fault, and land cover were obtained at the measurement points, they were then overlaid using the AHP statistical weighting method. The results of the overlay are then made a micro-zonation map of the potential for landslides based on these parameters along the South Bengkulu – Lahat road as shown in Figure 10.

Figure 11 shows that in micro-zonation the landslide potential consists of high landslide potential, medium landslide potential, and low landslide potential. The potential for landslides is more dominant in the study area which is spread evenly. The low potential for landslides is found in the central and northern regions of the study area. As for the high potential for landslides, it is only in the southern part of the study area. Based on the percentage, the area that has a low landslide potential is 26.87%. For medium landslide potential is 69.89% and for high landslide potential is 3.23% (Figure 12). In this study, the dominant factor that affects the magnitude of the high landslide potential is the GSS value associated with local rock conditions and the distance of the fault to the measurement point.

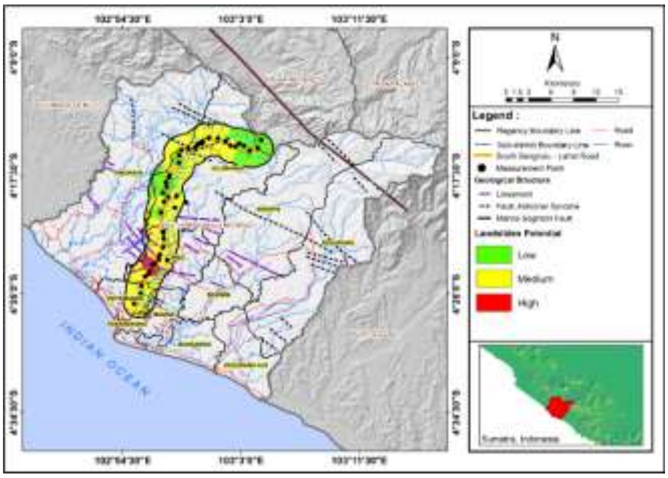

Figure 11. Micro-zonation map of the potential for landslides on the South Bengkulu–Lahat road, Bengkulu province

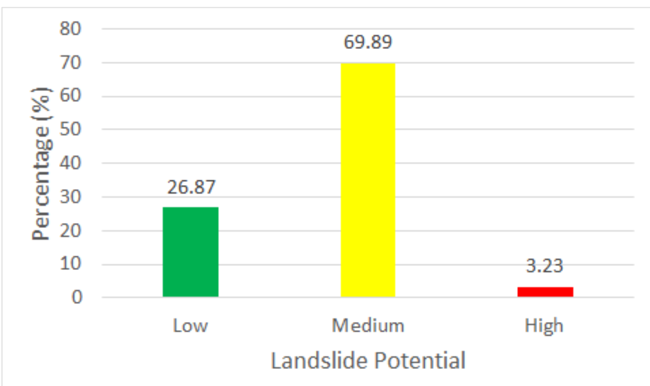

Figure 12. Percentage of potential landslides on the South Bengkulu–Lahat road, Bengkulu Province

Conclusion

This study can identify areas with high, medium, and low potential for micro-zonation based on statistical weighting of parameters such as rainfall, slope, GSS, PGA ground surface, Vs30, distance from measurement point to fault, and land cover obtained at the measurement points. The results showed that the area along the South Bengkulu–Lahat road had been identified microzoning high, medium, and low landslide potentials based on statistical weighting from parameters were obtained at the measurement points. For areas with high landslide potential, caution should be exercised, especially during the rainy season with high intensity and long duration. In areas with high landslide potential, it is also necessary to provide a landslide warning sign, so that people are more careful and alert when passing through the area. The results of this study should be used as a reference in the regional spatial plan of South Bengkulu regency, Bengkulu province, especially on the South Bengkulu – Lahat road. In addition, it is also necessary to conduct research studies on the potential for landslides with other parameters to strengthen or improve the results of this study.

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Author Contributions

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Conflicts of interest

There is no conflict of interest.

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