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Landslide Potential Investigation for Disaster Risk Reduction in Central Bengkulu Regency, Bengkulu Province, Indonesia

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Abstract – Bengkulu Province is the converging path region between the Indo-Australian – Eurasian tectonic plates in the ocean and the Sumatran fault crossing on the mainland. The condition implies that the sliding force of the slab is easy to trigger fractures and to cause the material to be relatively less elastic, resulting in high seismic intensity. This study aims to identify areas with the potential for landslides and its mapping, and to analyze the factors that cause landslides in Central Bengkulu Regency, Bengkulu Province, Indonesia. This study was conducted using rock physical parameters of ground shear strain (GSS) which were correlated with parameters of slope, slope height, Vs_{30} value, fault distance to measurement point, rock conditions, rainfall, and PGA value. Furthermore, these parameters were overlaid thoroughly by the statistical method of the Analytical Hierarchy Process (AHP). Data acquisition is divided into two stages, namely the secondary data collection stage and the field survey stage. Secondary data collection was carried out to support the creation of landslide potential maps, analysis, and field survey data input. Secondary data is the value of Vs_{30}, the distance of the fault to the measurement point, rainfall, and the PGA value. Field survey data are in the form of GSS values, slope, slope height, and rock conditions. The results of this study are identified areas that have the category of high, medium, and low landslide potential. Based on the calculated parameters, the GSS parameter is the most dominant which affects the landslide potential in the studied area.

Keywords: rock physical parameters of GSS, Vs_{30}, rainfall, PGA, statistical method of AHP

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Introduction

Background

Bengkulu Province is the converging path region between the Indo-Australian - Eurasian tectonic Plates in the ocean and the Sumatran Fault crossing the mainland. The results of study on seismicity in Sumatra Island show that the highest cumulative tectonic energy and strain rate values occur around the Bengkulu Province area. This can have implications for the movement of the slab glide force to easily trigger fractures that cause the material to be relatively less elastic, resulting in a high seismic intensity compared to other areas on the island of Sumatra (Murjaya, 2011, Megawati *et al*., 2005, and Irsyam *et al*., 2017).

The compression force of the Indo-Australian tectonic Plate and the Eurasian Plate has caused the Sumatran Fault System on the mainland to be divided into nineteen main segments (Bock *et al*., 2003; Gafoer *et al*., 2012; Sieh and Natawidjaya, 2000). Each segment has a different slip rate (Natawidjaya and Triyoso, 2007). One of the Sumatran Fault Systems cutting through Bengkulu Province is the Musi segment, which is located in Kepahiang Regency, bordering Central Bengkulu Regency.

Earthquake and high rainfall are the main factors that trigger landslides. The results of the study by Zhang *et al*. (2014) relating to the characterization of earthquakes caused by the movement of faults show that the earthquake in Wenchuan, China on May 12, 2008 with a magnitude of 7.9 and a depth of 19 km caused 322 shallow landslides around a road that is traversed by four faults and partially located on the hanging wall of the Yingxiu-Beichuan Fault. The magnitude of the earthquake and the volume of landslides from the earthquake that occurred in Chuya on September 27, 2003 with $Ms = 7.5$ and a depth of 18 km have an empirical relationship that the magnitude of the earthquake can increase the volume of the resulting landslide. This earthquake caused massive landslides and about three hundred houses were destroyed (Nepop and Agatova, 2008). Another example of landslides caused by earthquakes due to movement of faults is the earthquake in Papua New Guinea or 560 km northwest of the capital Port Moresby on February 26, 2018 with a magnitude of 7.6 SR and a hypocentre depth of 17 km. This earthquake occurred due to deformation activity in the New Guinea Highland (NGH) Fold and Thrust Belt which is an upward fault zone in the middle lane of the Papua New Guinea Mountains (Daryono, 2018).

Central Bengkulu is one of the regencies in Bengkulu Province, Indonesia, which is geographically located close to the source of earthquakes both at sea and on mainland, namely the Musi Segment Sumatra System. Regions that are close to the source of this earthquake are regions that have a potential to trigger landslides greater than other regions when an earthquake occurs (Hadi and Brotopuspito, 2015). According to Natawidjaya and Triyoso (2007), the frequency of repeated large earthquakes with a magnitude of ≥ 7 in the Musi Segment Fault is 165 years which is the highest among the Sumatran Fault segments in the Bengkulu region. Based on these conditions, Central Bengkulu Regency is vulnerable to earthquakes both at sea and on mainland. The average rainfall in Central Bengkulu Regency is also quite high, *i.e.* 2,673 mm/year (Anonymous, 2020a). This can happen because Central Bengkulu is one of intertropical convergence zones (ITCZ) which has high rainfalls throughout the year (Sudradjat, 2007).

Conditions with high seismicity in the sea and close to the Sumatra Fault of the Musi Segment on land, high rainfall, and steep slopes make Central Bengkulu Regency are very vulnerable and have the potential for landslides, especially in hilly areas. Based on these conditions, it is very interesting to investigate the potential for landslides in this area, because landslide prone points can be identified through mapping of potential landslides for disaster risk reduction.

This study aims to identify the areas with potential for landslides, to map the areas with potential for landslides, and to analyze the factors causing landslides in Central Bengkulu Regency, Bengkulu Province, Indonesia. This study was conducted using rock physical parameters of ground shear strain (GSS) as a parameter of ground deformation level related to landslide potential. To strengthen the parameters of the GSS value, it is necessary to use other factors that can contribute to landslides, namely the influence of geomorphological parameters in the form of slope and slope height, geological parameters in the form of Vs_{30}, geological structure (fault distance to measurement point), rock conditions, and external parameters such as rainfall and peak ground acceleration (PGA). Furthermore, all of these parameters are overlaid by the statistical method of the Analytical Hierarchy Process (AHP). AHP statistical method is used in this study because this method is a method of decision making to determine the best alternative from a number of alternatives based on certain criteria (Kusumadewi *et al*., 2006). This method describes a complex multifactors or multicriterion problem into a hierarchy. Hierarchy represents a complex problem in a multi-level structure consisting of objectives, followed by criteria, subcriteria, *etc.* to the last level of alternatives (Russo and Camanho, 2015). Based on the hierarchy of a complex problem, it can be broken down into groups which are then arranged into a hierarchical form, so that a problem will be more structured and systematic (Saaty *et al*., 1991). AHP is also a structured quantitative decision-making process that can be documented and replicated, can be applied as decision support for situations involving multicriteria, can be applied as decision support for situations involving subjective assessments, *etc.* (Steiguer *et al*., 2003).

Geological and Stratigraphical Settings

Part of the geological map of Bengkulu Quadrangle, Sumatra, as shown in Figure 1 (Gafoer *et al*., 2007) indicates that the predicted faults in this studied area are quite numerous and have a southwest-northeast and southeast-northwest orientations. The existence of these predicted faults will greatly affect the occurrence of landslides.

Stratigraphically, Central Bengkulu consists of Tertiary and Quaternary sequences. The Tertiary stratigraphic unit consists of Bintunan Formation (QTb), Simpangaur Formation (Tmps), Lemau Formation (Tml), Bal Formation (Tmba), Hulusimpang Formation (Tomh), Seblat Formation (Toms), and Diorit (Tmdi).

The rock units of Hulu Simpang Formation (Tomh) are the oldest rock unit in the studied area from the Late Oligocene to Middle Miocene. This formation was deposited in an intermediate environment between shallow land and marine. This formation interfingering with the Seblat Formation (Toms) is overlain by the Bal Formation (Tmba) and Lemau Formation (Tml). While the Bal Formation (Tmba) and Lemau Formation (Tml) are overlain by the Simpangaur Formation (Tmps). Furthermore, the Simpangaur Formation (Tmps) is overlain by the Bintunan Formation (QTb) (Gafoer *et al*., 2007 and 2012). The Diorite (Tmdi) intrudes the Hulusimpang Formation

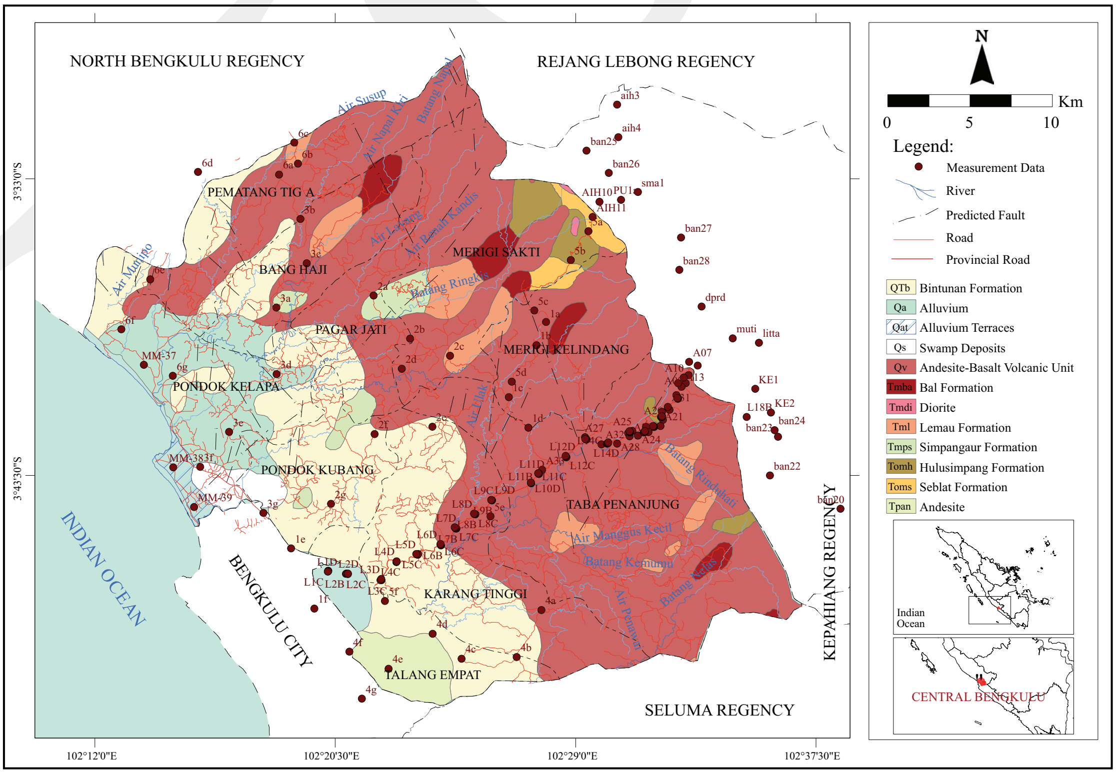

Figure 1. Regional geological map and measurement points at the studied site and its surrounding areas (Source: simplification from Geological Map of Bengkulu Quadrangle, Sumatra, scale 1:250,000; Gafoer *et al.*, 2007).

(Tomh) and it is overlain by Plistocene volcanic rocks. Weathering in this area is in the form of sandy clay rock, whitish gray, soft consistency, and high plasticity (Djadja *et al*., 2009).

The rock units contained in the Quaternary stratigraphy consist of Alluvium (Qa), Swamp Deposits (Qs), Alluvium Terraces (Qat), and Andesite-Basalt Volcanic Unit (Qv). Andesite-Basalt Volcanic Unit (Qv) is a Plistocene-Holocene volcanic rock comprising andesitic-basaltic lava, tuff, and volcanic breccia. Alluvium (Qa), Swamp Deposits (Qs), and Alluvium Terraces (Qat) are sedimentary rocks that are Holocene in age. Alluvium (Qa) is composed of boulders, pebbles, mud, and clays. Swamp Deposits (Qs) consist of sands, silts, muds, and clays containing plant remains, while Alluvium Terraces (Qat) comprise semiconsolidated gravels, sands, and mud-clays (Gafoer *et al*., 2012). The lithologies of the rock will have an effect in accordance with the conditions of its weathering level.

Methods

The data acquisition is divided into two stages, namely the secondary data collection stage and the field survey stage. Secondary data collection is carried out to support the creation of landslide potential maps, analysis, and field survey data input. Whilst the secondary data are in the form of topographic maps, regional geological maps, rainfall data, slope maps, landslide event data, average shear wave velocity data to a depth of 30 m (Vs_{30}), and PGA data. The field survey stage is microtremor data collection using the Horizontal to Vertical Spectral Ratio (HVSR) method. This method is used to determine the value of GSS. The output of the HVSR method is the amplification factor and predominant frequency. After obtaining the amplification factor and predominant frequency, the GSS value (γ) can be obtained at each measurement point. This relationship can be determined from the following equation (Nakamura *et al*., 2003; Nakamura, 2008).

$$\gamma = \left(\frac{A_g^{\,2}}{f_g}\right)\left(\frac{1}{\pi^2 V_b}\right) a_{\max} \quad \text{.....................(1)}$$

where:

A_g is the amplification factor,

f_g is the predominant frequency,

V_b is the shear wave velocity in basement (600 m/s), and

$a_{\max}$ is the PGA in basement.

PGA in basement is obtained from the relationship between changes in shear wave velocity in bedrock against time, while the calculation of the PGA value in basement uses the Probabilistic Seismic Hazard Analysis (PSHA) method. The calculation of the PGA value comes from the influence of subduction, fault, and shallow and deep background earthquake sources (Irsyam *et al*., 2010), so that the results can be analyzed comprehensively.

Taking the point of measurement in this study used the Broadband Seismometer PASI Gemini-2 with a triaxial geophone. Microtremor data collection refers to the standard Site Effects Assessment using Ambient Excitation (SESAME). The duration of data collection can give good results if the dominant frequency in the researched area is low enough. For this reason, data collection for each point is 30 minutes, assuming that during that time the data obtained are representative (Anonymous , 2004).

The microtremor data obtained in the field are still in the time domain. The HVSR technique is carried out by selecting the signal in the time zone (windowing). The determination of the window width refers to the SESAME European Research Project (Anonymous , 2004). After windowing, the conversion is transformed into the frequency domain using Fast Fourier Transform (Nakamura, 2000 and Daryono, 2011). In order to obtain the good data, a smoothing process is needed. The smoothing process in this study uses a bandwidth selection with a recommended coefficient value of 40 (Konno and Ohmachi, 1998).

The next data processing is in the form of HVSR curve analysis. The predominant frequency and amplification values obtained from the field are used as input parameters to produce the GSS value at ground level using Equation 1. The recorded microtremor data generated from the HVSR method were analyzed for the wave spectrum using win-MASW 5.2 HVSR software from PASI, Torino, Italy (Anonymous , 2013). In this programme, the reliability value can be found at each studied location as required by SESAME. However, the clear peak H/V values at several measurement points are not clearly visible, but in the win-MASW 5.2 HVSR software the values of A_g and f_g can be determined precisely. This phenomenon can occur due to the local geological conditions of the studied area.

Measurement points that have landslide potential based on the GSS value are then mapped as input parameters for the landslide potential distribution map. Furthermore, the slope obtained from the topographic map is processed to obtain the slope of each area in the studied location. The slope is also determined according to field conditions using a geological compass. After obtaining the parameters from the results of the analysis using the HVSR method and other rock physical parameters at each the measurement point, then they are overlaid thoroughly by the AHP statistical method.

The giving of the highest weight value for each given parameter is based on the main causes of landslides and the phenomenon of cases that occur in the field. The main causes of landslides come from physical properties of rocks are GSS and Vs_{30}. Other main causes of landslides are rainfall and earthquakes related to the distance of the fault to the measurement data and PGA, while the case phenomena occurring in the field are related to slope and slope height. Furthermore, rock conditions are related to the weathering degree of the rock at the measurement data point. The greater rating of the GSS value, rainfall, slope angle, slope height, and PGA gives the highest weight. The smaller Vs_{30} value ranking and the fault distance to the measurement data point give the highest weight, and the more weathered the rock also give the highest weight (Hadi, 2019).

Data interpretation is based on the GSS contour map overlaid by geomorphological parameters in the form of slope and slope height, geological parameters in the form of Vs_{30}, soil conditions, and geological structure (distance from the observation location to the fault), external parameters in the form of rainfall and PGA at the observation location. Regions that have slope angles, slope height, rainfall, PGA, high GSS value, low Vs_{30}, and locations close to faults are areas that have the potential for landslides. Based on the matching of the overlay GSS value with the parameters mentioned above using the AHP method, the potential for landslides from each measurement point can be identified. The final result of this activity is a map of landslide potential in Central Bengkulu Regency. On the landslide potential map, the highest score is an area that has the potential to experience landslides. Furthermore, from the analysis carried out, the factors causing landslides in the studied area can be seen from the parameters given in the weighting of the AHP method.

Results and Discussion

Secondary data in this study were obtained from several sources and related agencies, while the primary data obtained were 163 measurement points scattered in the researched site and its surrounding areas. For secondary data, annual rainfall data has been obtained in the Central Bengkulu Regency area during the 2015−2019 period from the Meteorological, Climatological, and Geophysical Agency of Bengkulu Province (Anonymous, 2020b). After obtaining the annual rainfall data in the studied area, a map of the distribution of annual rainfall was made as shown in Figure 2. This map can be used to determine the value of the annual rainfall at measurement points. The average annual rainfall in the studied area is between < 2,500 mm/year to > 3,500 mm/year. Areas that have rainfall of > 2,500 mm/

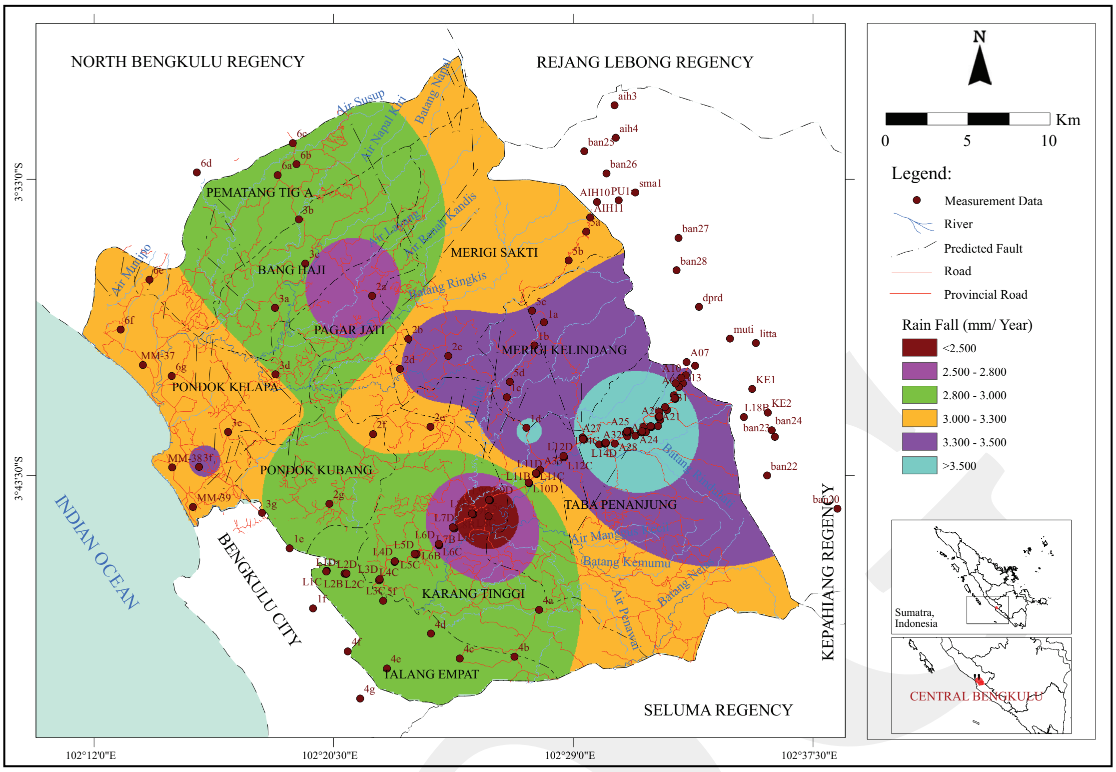

Figure 2. Average annual rainfall distribution map and measurement data in Central Bengkulu Regency and its surrounding areas, Bengkulu Province, Indonesia. The data were processed based on the average annual rainfall for the period of 2015−2019 from the Meteorological, Climatological, and Geophysical Agency of Bengkulu Province.

year have the potential to experience landslides (Kirmanto, 2007). The index class for rainfall is divided based on "Guidelines for Spatial Planning for Landslide Hazard Areas from the Ministry of Public Works of the Republic of Indonesia". Based on these guidelines, the low category is if the annual rainfall < 1,000 mm/year, the medium category is if the annual rainfall between 1,000 mm/year to 2,500 mm/year, and the high category is if the annual rainfall > 2,500 mm/year.

The regional geological map (Gafoer *et al*., 2007) was obtained from the Centre for Geological Survey of Bandung for Bengkulu Sheet. The Bengkulu Geological map was simplified for the studied area, namely Central Bengkulu Regency as shown in Figure 1. The map created was then overlaid by measurement points in the field. Furthermore, the Vs_{30} map obtained from the USGS and the PGA map obtained from the study of Hadi and Brotopuspito (2015) using the PSHA method, have been simplified for the studied site and its surrounding areas. The Vs_{30} and PGA maps were then overlaid by measurement points as shown in Figures 3 and 4.

Based on the geological map in Figure 1, the distance of the measurement points to the location of the fault is at least 6.07 m. Determination of measurement data points is based on local conditions and field access. From this case, the minimum fault distance to the measurement point obtained this value. The closer to these faults, the higher landslide potentials are if these faults move. A fault zone is a weak area where ground motion often takes place (Djadja *et al*., 2009). Areas that have experienced landslides at one time, will have the potential to experience landslides again, especially those near a fault (Hadi, 2019). For this reason, areas close to faults are given a high weight. The weighting for the fault distance category from the measurement points refers to the study of Hadi *et al*. (2018). Areas have the highest risk if the fault distance is less than 1

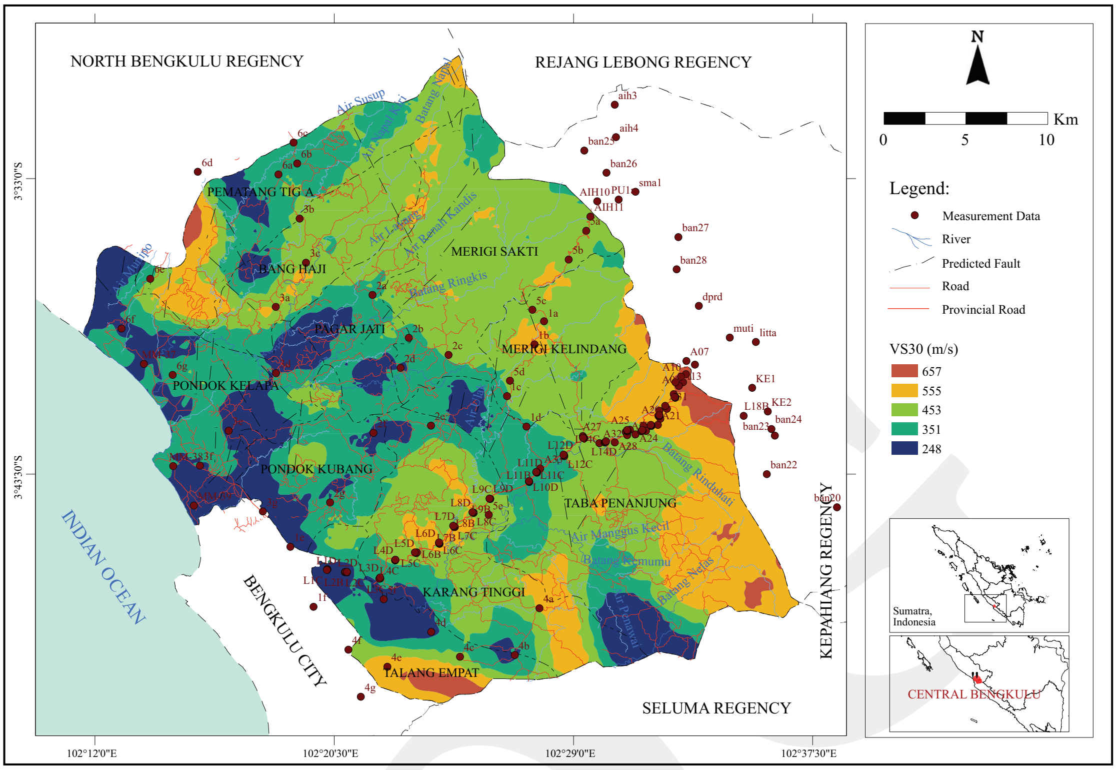

Figure 3. Vs30 distribution map and measurement data in Central Bengkulu Regency and its surrounding areas, Bengkulu Province, Indonesia. The map is created based on simplification of the USGS V_{s30} map (modification from Allen and Wald, 2007).

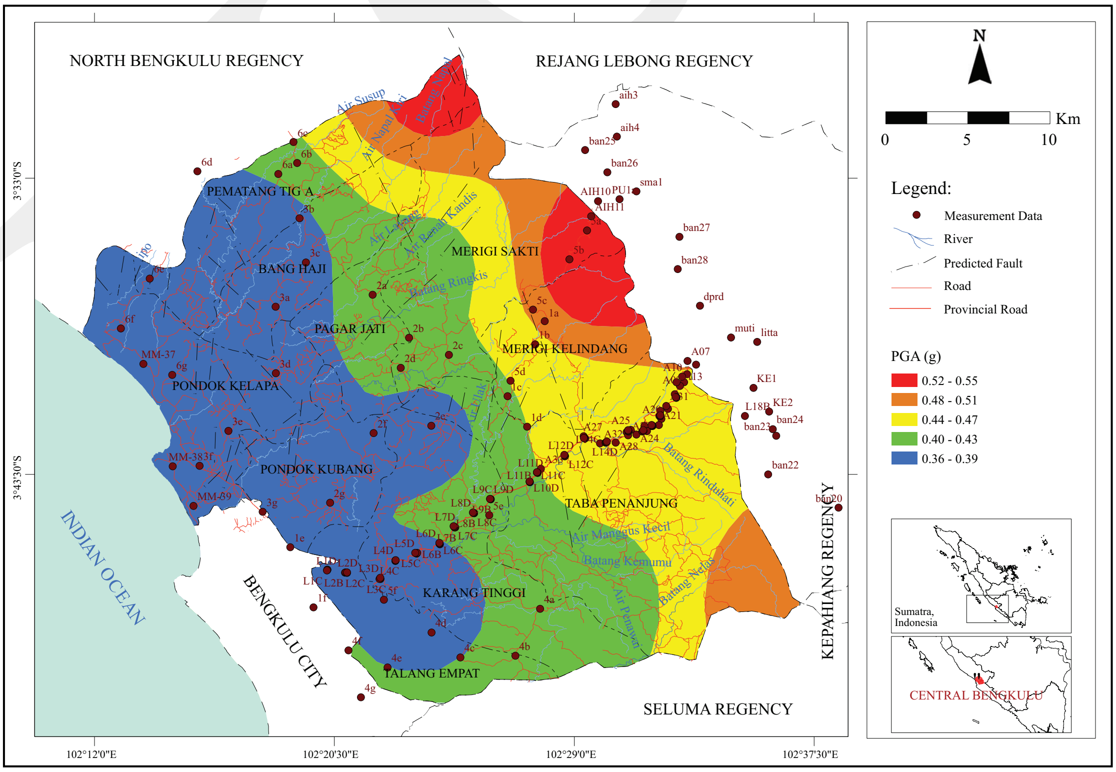

Figure 4. Map of PGA distribution and measurement data in Central Bengkulu Regency and its surrounding areas, Bengkulu Province, Indonesia (source: modification from Hadi and Brotopuspito, 2015).

km, medium risk if the fault distance is between 1 km to 5 km, and low risk if the fault distance is more than 5 km.

The Vs_{30} map obtained comes from USGS data with a grid between observation points of about 930 m (Figure 3). The use of the Vs_{30} map is based on a suitable correlation in an active tectonic area which has a greater match for the Vs_{30} value than in a stable area, *i.e.* ≥ 70% (Allen and Wald, 2007). For this reason, the USGS method using the topographic slope value as a proxy to obtain the Vs_{30} value is suitable for this researched area, and can be used for weighting values in this study.

The distribution value of Vs_{30} in Central Bengkulu Regency is 247 m/s − 657 m/s. Areas that have a lower Vs_{30} value are more at risk of earthquake threats. The speed of seismic waves passing through the rock depends on the hardness of a rock. The softer a rock, the lower the seismic wave speed in the rock, and vice versa (Hadi, 2019). In soft rock, the amplitude is bigger, so it is at risk of stronger shaking. Earthquake shocks in areas that have low Vs_{30} values can cause serious damage. If it occurs on a slope, there is a risk of landslides. The index class for the Vs_{30} category refers to SNI 1726-2012 (Anonymous , 2012a).

The PGA value obtained based on the PSHA approach in bedrock is between 0.36 g to 0.55 g. The magnitude of the PGA value is influenced by the presence of Sumatra Fault in the Musi segment which is located in the east and northeast of the city of Central Bengkulu. Areas with high PGA values are earthquake hazard zones. The areas with the highest PGA value are located in the northeast of Merigi Kelindang, Merigi Sakti, and Pematang Tiga Subregencies. The hazard classification of PGA value is based on the high, medium, and low categories (Anonymous, 2012b).

The slope map is obtained from the topographic map of the Geospatial Information Agency in the form of a 1:50,000 scale map and 1arc V.3 SRTM data analysis (Figure 5). The map is used as a comparison to field data in the form of slope angles measured directly. The slope index class refers to Zuidam (1983). He has divided slopes into seven grades from flat to steep (0° to > 55°). Steep slopes have a high risk of landslides. In this study, it is divided into three index classes, namely flat - moderately steep (< 25°), steep (25° - 40°), and very steep (> 40°).

The classification of rock conditions is based on the degree of weathering occurring in these rocks. The more weathered the rocks, the more prone to landslides. The fresher the rock, the fewer risk to landslides. In this study, the weighting of the rock condition class is divided into fresh rock which is very low at risk of landslides, medium rock conditions will have a low risk of landslides, whilst weathered rock conditions have a high risk of landslides. For slope height, the weighting criteria are based on phenomena occurring in the field. According to Hadi (2019), slope height ≥ 25 m has a high risk of landslides, slope height between 10 m - 25 m is at medium risk, and slope height ≤ 10 m has a low risk.

Measurement of field data using the HVSR method was carried out by mapping in the studied site and its surrounding areas. The distribution of measurement data at each measurement point can be seen in Figure 6. Field data acquisition is based on its accessibility. When taking HVSR data, measurements of slope height, slope angle, and rock condition were also carried out as input parameters for AHP data processing.

Based on the 163 measurement points at the field, the data that met the reliability criteria requirements of SESAME is obtained. An example of the microtremor data obtained in the field is shown in Figure 7. The data obtained from the field are the predominant frequency (f_g) and their amplification factor (A_g) as input to gain the GSS value at each measurement point. The value of the distribution of GSS at the studied location is shown in Figure 8.

The GSS distribution map shows that the range of GSS values is in the order of 10^{-3} , 10^{-2}, which is the value of moderate to high shear strain. The magnitude of the GSS value in the studied area is more dominantly influenced by the magnitude of

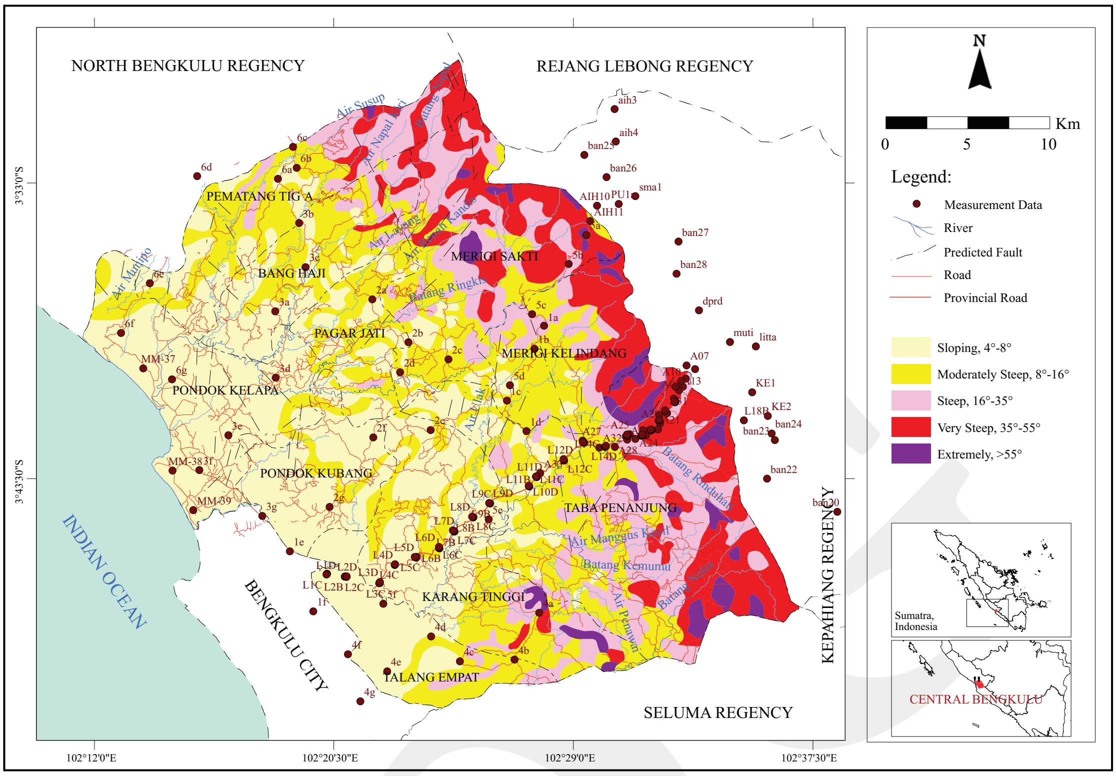

Figure 5. Slope map of the area of Central Bengkulu Regency, Bengkulu Province, Indonesia, with measurement data. The map is created based on the analysis of DEM SRTM 1arc V.3 data. Classification of slope classes refers to the division of slope classes according to Zuidam (1983).

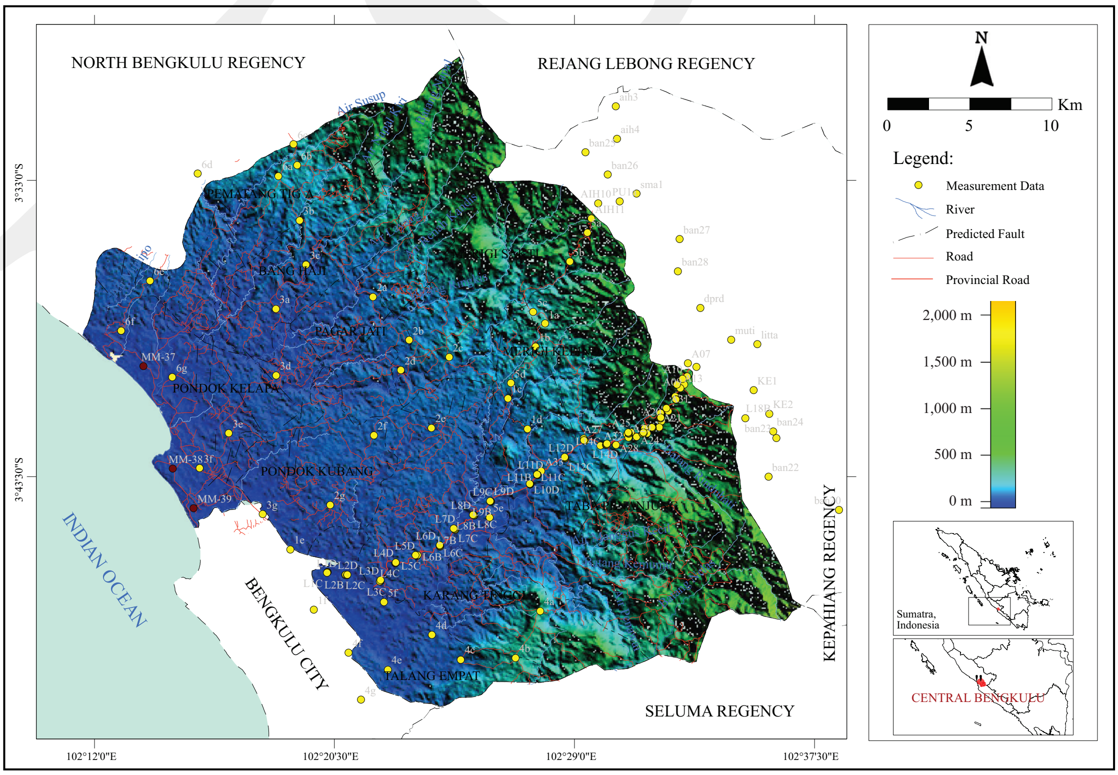

Figure 6. Distribution of measurement data in the studied area. The map is created based on the analysis of DEM SRTM 1arc V.3 data.

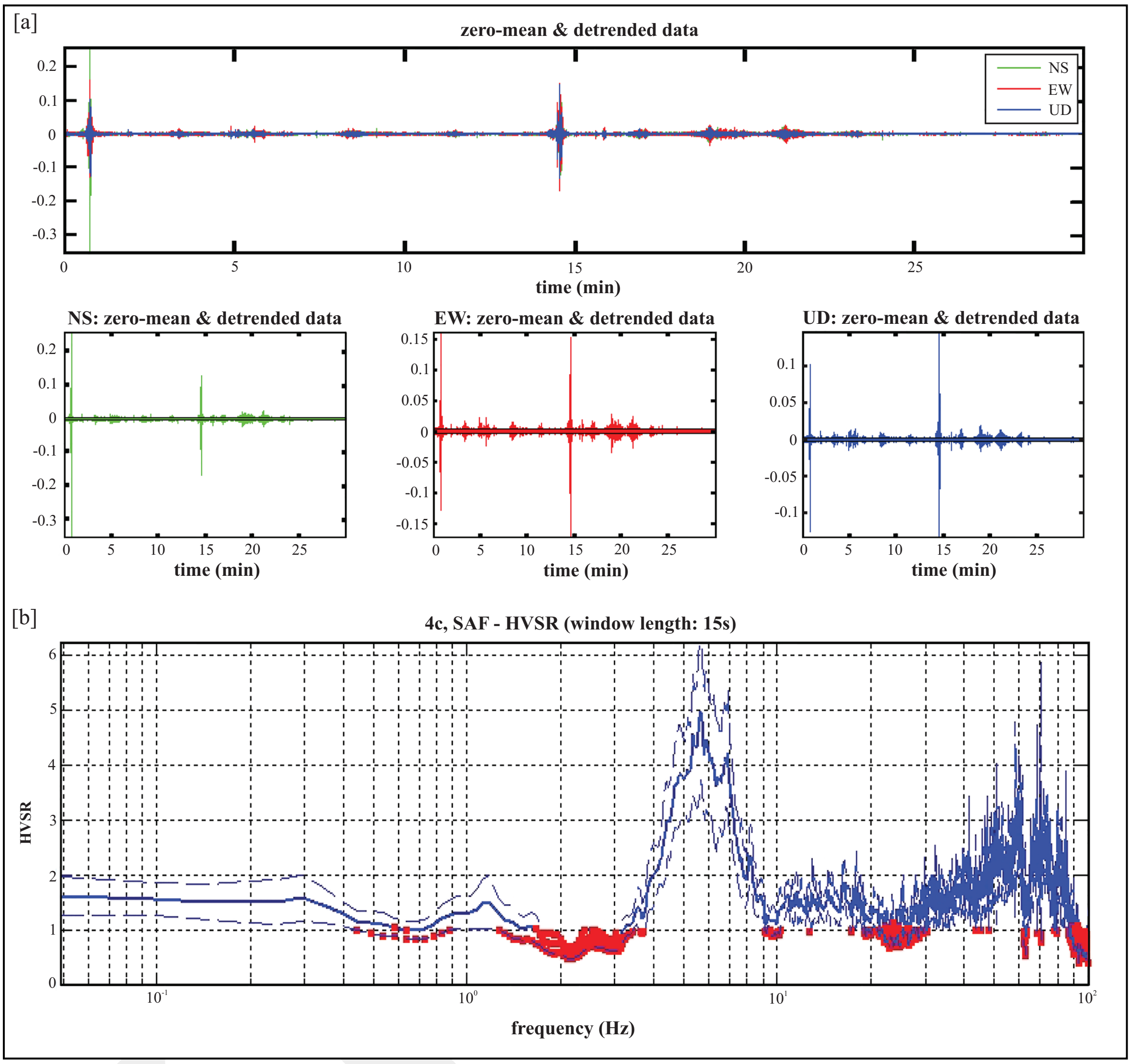

Figure 7. An example of recording microtremor data at measuring point 4c with a triaxial geophone. (a) North-South (NS) direction, East-West (EW) direction, up-down (UD) direction and (b) Results of microtremor data processing at the 4c measurement point with the predominant frequency (f_g) value is 5.7 (±3.1) and amplification factor (A_g) value is 5.0 (±1.2).

the PGA value. The high PGA value in the studied area which is an active fault area also contributes to the high GSS value (Hadi, 2019). However, for locations that far from active faults, the magnitude of the PGA value is much influenced by the magnitude of the amplication factor (A_g) and the thickness of the sediments or its dominant frequency (f_g). At the measurement location, a high amplification value and low dominant frequency are obtained. At the studied location, if an earthquake shakes occur, the rock with the greater the GSS value will easily be deformed. The weighted classification is based on the range of GSS values, where the low is < 10^{-4}, medium is $10^{-4} - 10^{-3}$, and high is $10^{-2} - 10^{-1}$ (Ishihara, 1996 and Oliveira *et al*., 2008).

After obtaining all secondary data and primary data, then these parameters are overlaid thoroughly using the AHP statistical method. AHP calculation of the overlaid parameters and sub-parameters is shown in Table 1. Weighting values are based on the greatest influence on landslides. The greatest influence on landslide incidence in this study, is derived from GSS, Vs_{30}, rainfall, slope angle, slope height, fault distance to measurement data, PGA, and rock conditions (Hadi,

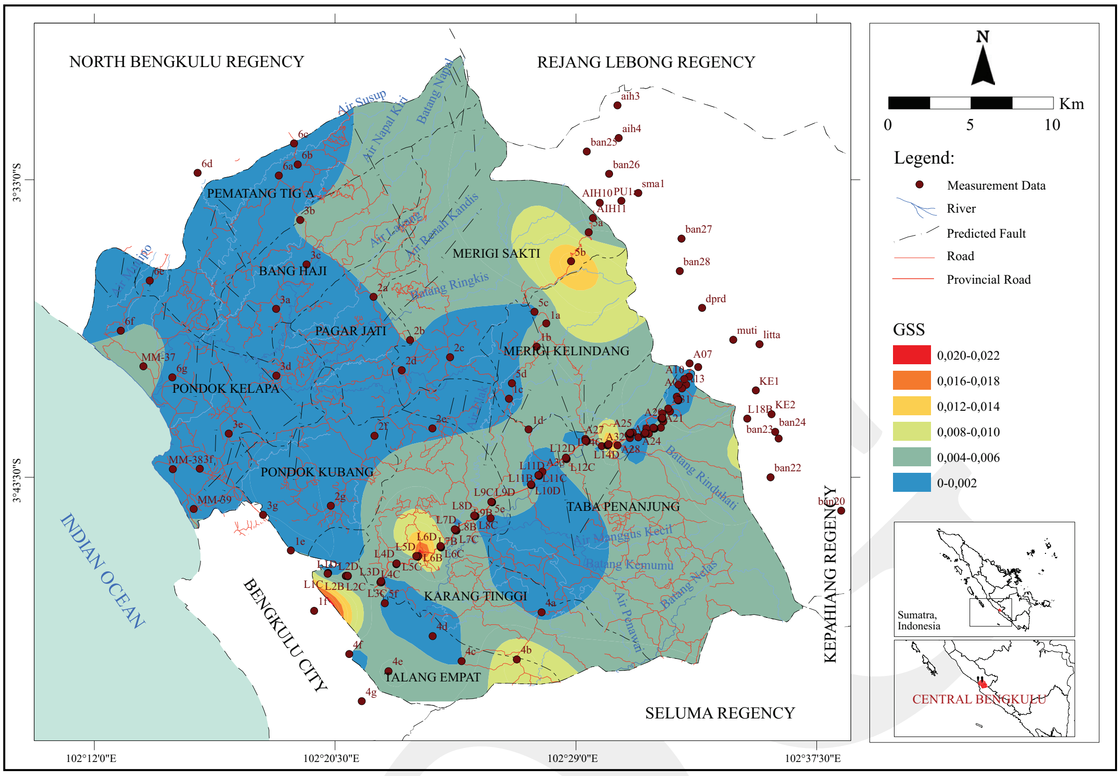

Figure 8. GSS distribution map and measurement data in Central Bengkulu Regency, Bengkulu Province, Indonesia.

2019). For this reason, these parameters give the highest to lowest weight. Furthermore, each of the parameter involved make a pair comparison matrix according to the weights influencing each other, and the preference value of each decision is determined based on the respective criteria weight (Saaty, 1980).

After determining the scale of comparison for each given parameter and subparameter, a ranking is made by calculating the total score, namely the multiplication of the relative weight of the parameter and the relative weight of the subparameter at each measurement point as shown in Table 2. The relative weight of the parameters is obtained from the pairwise comparison matrix for each parameter as in Table 1. The relative weight of the sub-parameters is determined based on the results of studies that have been

Table 1. Pairwise Comparison Matrix for Each Parameter

Parameter	GSS	Rainfall (mm/yr)	PGA (g)	V_{s30} (m/s)	Slope (°)	Fault distance (km)	Rock conditions	Slope height (m)
GSS	1	5	7	3	5	5	7	5
Rainfall (mm/yr)	1/5	1	3	1/3	1	1	3	1
PGA (g)	1/7	1/3	1	1/5	1/3	1/3	1	1/3
V_{s30} (m/s)	1/3	3	5	1	3	3	5	3
Slope (°)	1/5	1	3	1/3	1	1	3	1
Fault distance (km)	1/5	1	3	1/3	1	1	3	1
Rock conditions	1/7	1/3	1	1/5	1/3	1/3	1	1/3
Slope height (m)	1/5	1	3	1/3	1	1	3	1

Table 2. Weights of Each Parameter and Subparameter Calculated Using the AHP Method

Parameter	Relative weight	Sub-parameter	Relative weight
GSS	0.38	GSS ≥ 10^{-2}	0.63
		10^{-4} < GSS < 10^{-2}	0.26
		GSS ≤ 10^{-4}	0.11
Rainfall (mm/yr)	0.09	Rainfall > 2500 mm/th	0.63
		1000 mm/th ≤ Rainfall ≤ 2500 mm/th	0.26
		Rainfall < 1000 mm/th	0.11
PGA (g)	0.03	PGA ≥ 0.7 g	0.63
		0.26 g ≤ PGA < 0.7 g	0.26
		PGA < 0.26 g	0.11
V_{s30} (m/s)	0.21	V_{s30} < 350 m/s	0.63
		350 m/s ≤ V_{s30} < 750 m/s	0.26
		V_{s30} ≥ 750 m/s	0.11
Slope (°)	0.09	Very steep > 40°	0.63
		Steep, 25°- 40°	0.26
		Flat - moderately steep, < 25°	0.11
Fault distance (km)	0.09	Fault distance < 1 km	0.63
		1 km ≤ Fault distance < 5 km	0.26
		Fault distance ≥ 5 km	0.11
Rock conditions	0.03	Weathered	0.63
		Moderate weather	0.26
		Fresh	0.11
Slope height (m)	0.09	Slope height ≥ 25 m	0.63
		10 m ≤ Slope height < 25 m	0.26
		Slope height < 10 m	0.11

conducted by previous researchers. The relative weights of the GSS subparameters are derived from the studies of Ishihara (1996) and Oliveira *et al*. (2008). According to both geologists, soil layer with low GSS values ≤ 10^{-4} to medium (10^{-4} - 10^{-3}) only experiences vibration until settlement and is still elastic to plastic. While soil with high GSS values ≥ 10^{-2} can experience compaction, so it can cause landslides or liquefaction and has a soil dynamic characteristic of collapse. The relative weight of the subparameter of rainfall comes from the Kirmanto's study (2007). According to him, an average rainfall of > 2,500 mm/year has the potential to cause high landslides, so rainfall of > 2,500 mm/year gives the highest weight. Furthermore, the National Disaster Management Agency of the Republic of Indonesia divides the hazard category from PGA in the form of low PGA values (PGA < 0.26 g), medium PGA (0.26 g ≤ PGA < 0.7 g), and high PGA (PGA ≥ 0.7 g), so the PGA value ≥ 0.7 g gives the highest weight (Anonymous, 2012b). The weighting for the V_{s30} subparameter refers to SNI 1726:2012 (Anonymous, 2012a) where a low V_{s30} value is more at risk of earthquakes and landslides. Based on these criteria, the value of V_{s30} gives the highest weight.

The subparameters of slope and slope height are given weight based on the phenomena occurring in the field. The phenomena that occur in the field show that slope angle > 40° and slope height ≥ 25 m have experienced large landslides, so the highest weight is given. The weighting of the distance of the fault to the measurement point is based on the criteria that the closer the fault to the measurement point, the more damage that location suffers on the event of an earthquake. Thus, the closest distance to the fault gives the highest weight. For rock conditions, the weighting is based on the criteria that the more weathered the rock, the easier it deforms. Thus, the highest weight is given.

The average consistency ratio (CR) value obtained from the AHP calculation is ≤ 0.1. If the CR value is ≤ 0.1, then the calculation results on the AHP method will be considered the consistent and accepted. The multiplication result between the relative weights of each parameter and subparameter is used to select the alternative with the highest score (Kusumadewi *et al.*, 2006).

The landslide potential values at each measurement point obtained are then searched for the class intervals to determine the landslide potential category. The results of weighting calculations using the AHP statistical method of the rock physical parameters are divided into three categories, namely for the category of high landslide potential with a value between 0.43−0.53 (red colour), medium landslide potential with a value between 0.32 - 0.43 (yellow colour), and low landslide potential with a value of 0.22 - 0.32 (green colour). Based on these values, a landslide potential map of the studied area is obtained based on rock physical parameters and AHP for disaster risk reduction in Central Bengkulu Regency, Bengkulu Province, Indonesia, as shown in Figure 9.

Most of the potential landslides in the studied area are in the medium potential category. There is a high potential for landslides in almost all studied areas, but the locations are at certain points, especially in hilly areas. Regions that have a high potential for landslides must be controlled, especially in residential areas as well as on roads or connecting roads, for example provincial roads that connect other cities. Central Bengkulu Regency is a relatively new developing area, so disaster mitigation in this area is very necessary as a mean of disaster risk reduction and better future spatial and regional planning.

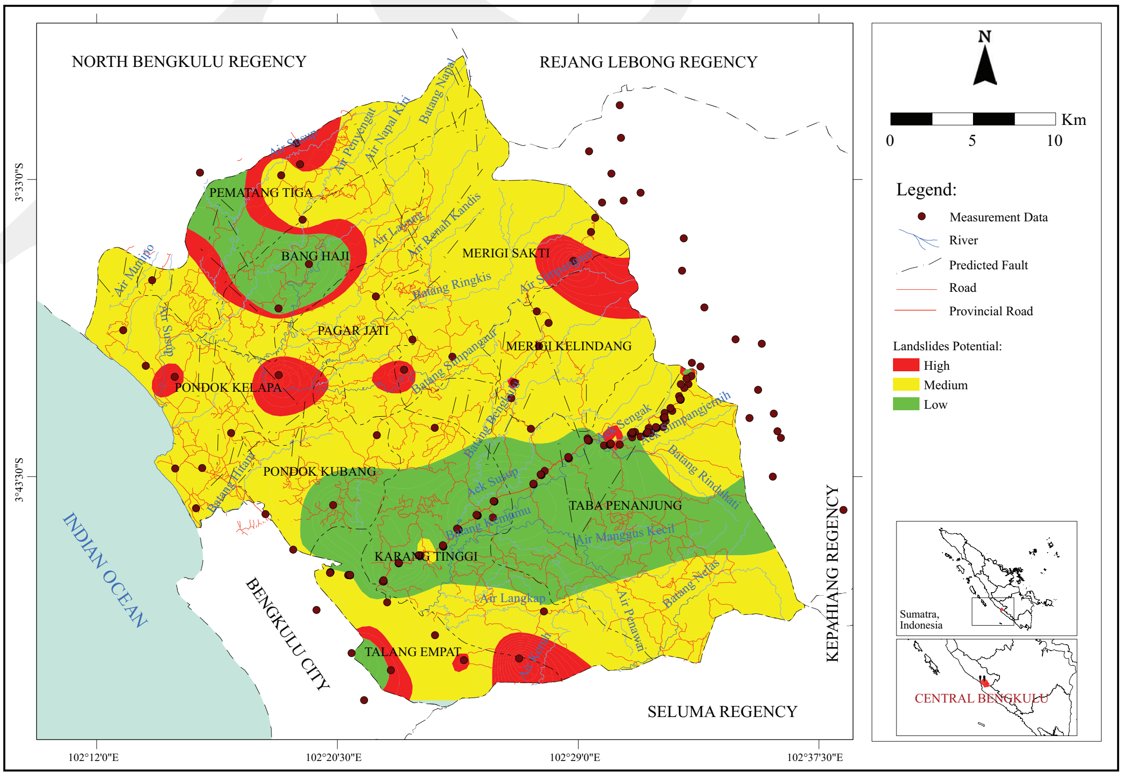

Figure 9. Landslide potential map of Central Bengkulu Regency, Bengkulu Province, Indonesia, based on rock physical parameters and AHP statistical methods.

Conclusions

This study has produced a landslide potential map based on rock physical parameters such as GSS, slope angle, slope height, Vs_{30}, fault distance to measurement point, rock conditions, rainfall, and PGA overlaid using the AHP method. The results of this study have also identified the areas that have the category of high landslide potential, medium landslide potential, and low landslide potential.

Areas with high potential are in Merigi Kelindang, Merigi Sakti, Pagar Jati, Pematang Tiga, Bang Haji, Pondok Kelapa, Taba Penanjung, Talang Empat, and Karang Tinggi Subregencies. Medium landslide potential is located in all subregencies, while areas with low potential are in Pematang Tiga, Bang Haji, Pondok Kubang, Taba Penanjung, Karang Tinggi, and Talang Empat Subregencies. Based on the calculated parameters, the GSS parameter is the most dominant which affects the landslide potential in the studied area. This can be seen on the GSS distribution map which has a similar trend to the landslide potential map. The magnitude of the GSS value is also influenced by the magnitude of the PGA value and rock conditions in the studied area.

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